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(54) Title: SOUND SYSTEM AND METHOD OF SOUND REPRODUCTION

(57) Abstract: A sound reproduction system comprises a left and right speakers located in close proximity, and a sound processor which provides audio signals to the pair of speakers. The sound processor preferably derives a cancellation signal from the difference between the left and right channels. The resulting difference signal is scaled, delayed (if necessary), and spectrally modified before being added to the left channel and, in opposite polarity, to the right channel. The spectral modification to the difference channel preferably takes the form of a low-frequency boost over a specified frequency range, in order to restore the correct timbral balance after the differencing process. Additional phase-compensating all-pass networks may be inserted in the difference channel to correct for any extra phase shift contributed by the spectral modifying circuit. The technique may be used in a surround sound system or an automobile sound system. In an automobile, the pair of speakers may be placed together in a common enclosure having a narrow slot near the base of the cone of the speakers. The speaker may be oriented perpendicularly with respect to the dashboard such that the sound emanates from the slot in the enclosure.



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## SOUND SYSTEM AND METHOD OF SOUND REPRODUCTION

### BACKGROUND OF THE INVENTION

5     1) Field of the Invention

**[0001]**       The field of the present invention relates to sound reproduction and, more specifically, to a speaker configuration and related sound processing for use in a sound system.

10    2) Background

**[0002]**       Attaining optimal sound quality in surround sound or multi-channel sound systems, over the largest possible listening area, can be quite challenging. Some of the difficulties in achieving optimal sound quality in such systems result from the fact that a wide variety of different surround sound and multi-channel audio formats and speaker configurations exist, so that a particular sound system may have reasonably acceptable sound with respect to one or perhaps two audio formats yet sub-optimal sound with respect to other audio formats. Therefore, where a consumer desires, for example, to use a single sound system to play sound recordings in a variety of different formats, different levels of sound quality, some of which are poor or impaired, are likely to be experienced. While the user can adjust speaker positioning or relative balances to try to

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improve sound quality, such techniques may involve significant manual effort or inconvenience, may be hard to reproduce consistently, and may benefit only one or perhaps a few listeners in a relatively small portion of the listening area.

**[0003]** Existing surround sound recording formats include those referred to as

5 5.1, 6.1 and 7.1. The 5.1 surround format comprises a compressed data stream containing five channels, generally designated left, center, right, surround left, and surround right, named for the speaker positions for which the channel information is intended. A low frequency effects channel is formed by a combination of the five other channels, and may be provided to a sub-woofer. The 6.1 surround format includes the  
10 same five channels as the 5.1 surround format, but adds a surround back channel, which may be fed to one or more back speakers in a surround sound system. The 7.1 surround format is similar to the 6.1 surround format, but has two surround back channels (surround back left and surround back right) rather than a single back channel, for a total of seven channels. Thus, the 5.1 surround format has two surround channels (surround  
15 left and right), the 6.1 surround format has three surround channels (surround left, right and back), and the 7.1 surround format has four surround channels (surround left and right, and surround back left and right).

**[0004]** Basic surround system speaker configurations generally include from six

to eight speakers placed at conventionally well-established locations, according to the  
20 type of surround format they are intended to play. A six-speaker surround system typically includes left, right and center speakers (with the right and left speakers spaced widely apart), a sub-woofer, and surround left and right speakers (which may be monopolar or dipolar in nature). A seven-speaker surround system typically includes

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the same speaker arrangement as the six-speaker surround system, but adds a back surround speaker. An eight-speaker surround system typically includes the same speaker arrangement as the six-speaker surround system, but adds a back left surround speaker and a back right surround speaker.

5     **[0005]**       The enjoyment experienced by a listener in a surround sound system can be affected by a number of factors, including the listener's physical position relative to the various speakers, as well as by the particular format of the audio track being played on the system. For example, when a 5.1 surround format soundtrack is played on an eight-speaker (7.1) surround system, certain anomalies may occur. An example is that, if  
10    the 5.1 surround left and surround right audio signals are monaural, then the left and right surround effects can disappear, being replaced by a single central "phantom" sound image at the rear. Another phenomenon is that if the listener is positioned in the middle of the surround left and surround right speakers, he or she may perceive the surround left and right sound (if monaural) to be higher in volume than it otherwise  
15    would be, primarily due to the additive effect of the sound waves intersecting at the listener's position (known as a "lift" effect). If the sound pans from one side to the other (e.g., from left to right), the sound volume may appear to increase as left/right balance is achieved, and then appear to decrease as the sound continues to pan, even though the audio output level remains constant, due to the same "lift" effect. The sound  
20    quality may also seem to be "unstable," in the sense that if the listener moves from the center position, the sound might seem to "flip" from one side to the other.

**[0006]**       Some of these effects can be mitigated in 5.1 surround sound systems by the use of adaptive de-correlation with respect to the surround left and right speakers,

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which derives two substantially de-correlated signals when the surround left and right signals are monaural, in order to provide an improved enveloping surround effect.

**[0007]** When a 6.1 surround format soundtrack is played on an eight-speaker (7.1) surround system, certain other anomalies may be experienced. Since the two rear surround speakers (left and right) are each fed with an identical monaural signal (that is, the same surround back signal), a centrally located “phantom” image may result when the listener is positioned approximately equidistant from the speakers. Reported side effects of this arrangement include “coloration” associated with the phantom image (for example, the sound may seem “unnatural”), a narrow “sweet spot” due to lack of sound image stability when the listener moves off center, and a comb filter effect (in other words, nulls may be produced due to sound wave cancellation effects).

**[0008]** Besides surround systems, a variety of multi-channel recording and playback systems also exist. Examples of some common multi-channel sound systems are Dolby AC-3, DTS, and DVD-Audio, each of which has its own specific digital encoding format. Unlike cinema sound, there is generally no single adopted standard of either loudspeaker type (e.g., full range, satellite plus sub-woofer, dipole, monopole) or speaker layout for most multi-channel audio formats. Any user therefore desiring to listen to multi-channel soundtracks, and/or any of the surround formats (5.1., 6.1 and 7.1), is required either to accept one speaker layout optimized for a particular audio format and experience a compromised performance for all others, or to reconnect various speakers to suit the audio format a particular soundtrack.

**[0009]** Beyond the surround sound environment, other sound systems also face similar challenges, such as attaining a suitably wide “sweet spot” in which the

perceived area and stability of a stereo sound image is maximized. In most traditional sound systems, the convention has been to place left and right speakers far apart physically, under the theory that the human ear is thereby better able to perceive the richness of the audio subject matter. However, under many left/right speaker configurations, the sound at off-axis listening positions may be sub-optimal. The quality of sound at a given off-axis listening position may be affected not only by the difference between left and right volumes resulting from the different distances to the left and right speakers, but also by the slight difference in time it takes the aural information to reach the listener.

10 **[0010]** Accordingly, it would be advantageous to provide an improved sound system which overcomes one or more of the foregoing problems or shortcomings.

#### SUMMARY OF THE INVENTION

**[0011]** The present invention is generally directed to improved sound reproduction systems and methods involving a speaker configuration and/or placement, and related sound processing, for enlarging the perceived area and stability of a sound image generated from right and left source signals.

**[0012]** In one aspect, a sound reproduction system comprises a pair of speakers (left and right) located in close proximity, and a sound processor which provides audio signals to the pair of speakers. According to a preferred embodiment, the sound processor acts to "spread" the sound image produced by the two closely spaced speakers by employing a cross-cancellation technique wherein a cancellation signal is derived, for example, from the difference between the left and right channels. The

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resulting difference signal is scaled, delayed (if necessary) and spectrally modified before being added to the left channel and, in opposite polarity, to the right channel. The spectral modification to the difference channel preferably takes the form of a low-frequency boost over a specified frequency range, in order to restore the correct timbral balance after the differencing process which causes a loss of bass when the low-frequency signals in each channel are similar. Additional phase-compensating all-pass networks may be inserted in the difference channel to correct for any extra phase shift contributed by the usually minimum-phase-shift spectral modifying circuit so that the correct phase relationship between the canceling signal and the direct signal is maintained over the desired frequency range.

**[0013]** Alternatively, a linear-phase network may be employed to provide the spectral modification to the difference channel, in which case compensation can be provided by application of an appropriate, and substantially identical, frequency-independent delay to both left and right channels.

**[0014]** The various speaker configuration and sound processing embodiments as described herein may be employed in connection with a surround sound system to achieve improved sound reproduction. A sound reproduction system for a surround sound stereophonic system may comprise a set of speakers (e.g., front, left, center, surround left, and surround right), including a pair of surround back speakers located in close proximity, and a sound processor. The sound processor receives left and right surround channel signals (either side or rear surround signals), and generates a difference signal therefrom. The resulting difference signal may be processed as described above – i.e., scaled, delayed (if necessary) and spectrally modified before

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being added to the left channel and, in opposite polarity, to the right channel. Additional phase-compensating all-pass networks may, as noted above, be inserted in the difference channel to correct for any extra phase shift contributed by the usually minimum-phase-shift spectral modifying circuit so that the correct phase relationship  
5 between the canceling signal and the direct signal is maintained over the desired frequency range.

**[0015]** In the automobile or vehicle context, the pair of central speakers may be placed in a common enclosure with a central dividing partition that is inserted into or else integral with the front console or dashboard of the automobile. In certain  
10 embodiments, the center speakers may be placed with their diaphragms facing down and in close proximity to a rigid reflecting surface such that substantially all of the sound energy is directed forward, towards the listener, via an arrow slot in the enclosure. The resultant radiating system provides the dual benefit of occupying less dashboard area, where space is always at a premium, and possessing a very wide directional  
15 characteristics due to the slot having dimensions that can be made very small with respect to the wavelength the radiated sound.

**[0016]** Further embodiments, variations and enhancements are also disclosed herein.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0017]** FIG. 1 is a diagram illustrating playback of a soundtrack in a 5.1 surround  
20 system.

**[0018]** FIG. 2 is a diagram illustrating playback of a 5.1 surround format soundtrack in a 7.1 surround sound system.

**[0019]** FIG. 3 is a diagram illustrating playback of a 6.1 surround format soundtrack in a 7.1 surround sound system.

5 **[0020]** FIG. 4 is a diagram illustrating the concept of a "sweet spot" in the context of 6.1 surround format playback in a 7.1 surround sound system.

**[0021]** FIG. 5 is a diagram illustrating movement of the phantom image in conjunction with the listener's movement.

**[0022]** FIG. 6 is a diagram of a speaker configuration for a surround sound  
10 system, in accordance with a preferred embodiment as described herein.

**[0023]** FIG. 7 is a diagram illustrating 6.1 surround format playback in the surround sound system shown in FIG. 6.

**[0024]** FIG. 8 is a simplified block diagram of a sound processing system in accordance with one or more embodiments as disclosed herein, as may be used, for  
15 example, in connection with the speaker configuration illustrated in FIG. 6.

**[0025]** FIG. 9-1 is a more detailed diagram of a sound processing system as may be used, for example, in connection with the system illustrated in FIG. 6

**[0026]** FIG. 9-2 is a diagram of a sound processing system in general accordance with the layout illustrated in FIG. 9-1, further showing examples of possible transfer  
20 function characteristics for certain processing blocks.

**[0027]** FIG. 10 is a diagram of a sound processing system illustrating representative transfer functions.

**[0028]** FIG. 11 is a diagram of a sound system in accordance with the general principles of the systems illustrated in FIGS. 8 and 9, as applied in the context of a surround sound system.

**[0029]** FIG. 12 is a conceptual diagram illustrating processing/operation for 5.1 surround format playback in the context of a surround sound system such as shown, for example, in FIG. 6 or 11.

**[0030]** FIGS. 13 and 14 are graphs illustrating examples of frequency response and phase transfer functions for a sound processing system having particular spectral weighting and other characteristics.

**[0031]** FIGS. 15-1, 15-2, and 15-3 are graphs illustrating examples of gain and/or phase transfer functions for a sound processing system in accordance with FIG. 9-2.

**[0032]** FIG. 16 is a diagram of a sound processor employing a linear spectral weighting filter.

**[0033]** FIG. 17 is a diagram of a preferred automobile sound system in accordance with one or more embodiments as disclosed herein.

**[0034]** FIG. 18 is a diagram of a surround sound system for an automobile or other vehicle.

**[0035]** FIGS. 19-1, 19-2 and 19-3 are diagrams illustrating possible placement of a pair of center speakers.

**[0036]** FIG. 20-1 is a front cut-away view of a preferred speaker enclosure for a pair of stereo speakers.

**[0037]** FIG. 20-2 is a top cross-sectional view of the speaker enclosure shown in FIG. 20-1.

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[0038] FIG. 20-3 is an oblique front view of the speaker enclosure shown in FIGS. 20-1 and 20-2.

[0039] FIG. 20-4 is a diagram illustrating sound reflection from a downward oriented speaker, such as a speaker in the speaker enclosure of FIGS. 20-1 through 20-3.

5 [0040] FIG. 21 is a block diagram illustrating an example of an automobile sound system for providing potentially improved extreme right/left sound, in connection with the pair of closely spaced center speakers.

[0041] FIG. 22 is a graph illustrating a relationship between speaker separation in various embodiments as disclosed herein and difference channel gain.

10 [0042] FIG. 23 is a diagram of another embodiment of a surround sound system for an automobile or other vehicle.

[0043] FIGS. 24-1 and 24-2 are diagrams comparing the audio effect of speaker placement and sound processing between the prior art and various embodiments as disclosed herein.

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#### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0044] According to various embodiments as disclosed herein, a preferred sound reproduction system comprises, in one aspect, a pair of speakers located in close proximity, and a sound processor which provides audio signals to the pair of speakers.

20 The sound processor preferably acts to "spread" the sound image produced by the two closely spaced speakers by employing a cross-cancellation technique wherein a cancellation signal is derived, for example, from the difference between the left and right channels. The resulting difference signal is scaled, delayed (if necessary) and

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spectrally modified before being added to the left channel and, in opposite polarity, to the right channel, thereby enlarging the perceived area and stability of the stereo sound image. Further details of preferred sound processing techniques are described later herein.

5   **[0045]**       Some advantages of various embodiments disclosed herein can be appreciated by way of contrast and comparison with conventional surround/multi-channel sound systems. FIG. 1, for example, is a diagram illustrating playback of a surround-encoded soundtrack in a 5.1 surround system 100. As shown in FIG. 1, the 5.1 surround system 100 includes a front left speaker 104, a front right speaker 105, a  
10   center speaker 102, a sub-woofer 109, a surround left speaker 114, and a surround right speaker 115. In the example shown in FIG. 1, the surround left and right speakers 114, 115 are both dipolar speakers, which distribute sound in multiple (typically opposite) directions and are thereby provide improved ambient sound. The surround left and right speakers 114, 115 are typically widely spaced on opposite sides of a room (or  
15   other listening space), at positions which are above and slightly to the rear of the desired listening position.

**[0046]**       The speakers 102, 104, 105, 109, 114, and 115 in the 5.1 surround system 100 are generally arranged to provide optimum sound for a listener 107 positioned in the approximate center of the speaker arrangement. However, a 5.1  
20   surround system lacks an effective directional component to the immediate left and right sides and to the rear of the listener 107. Therefore, a 6.1 or 7.1 surround system, both of which have a rear speaker component, is generally capable of providing superior sound and audio effects in certain contexts. A 6.1 surround system, as previously

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indicated, adds a single rear surround speaker, while a 7.1 surround system adds two rear surround speakers typically spaced relatively far apart from one another.

**[0047]** FIG. 2 is a diagram of a 7.1 surround system 200, illustrating playback of a 5.1 surround-encoded soundtrack. As shown in FIG. 2, the 7.1 surround system 200 includes front left and right speakers 204, 205, a center speaker 202, a sub-woofer 209, a surround left speaker 214, a surround right speaker 215, a surround back left speaker 224, and a surround back right speaker 225. In the particular example of FIG. 2, as with FIG. 1, the surround left and right speakers 214, 215 are dipolar in nature. The surround back left and right speakers 224, 225 are typically spaced relatively far apart behind the listener 207. When a 5.1 encoded soundtrack is played on a 7.1 surround system 200 such as shown in FIG. 2, the surround left and right speakers 214, 215 receive the left and right surround channel information, and the surround back left and right speakers 224, 225 may or may not receive the left and right surround channel information, depending upon how the user has programmed the system 200. In either case, certain anomalies can occur. For example, if the left and right surround channels are monaural, the left/right surround effect can seem to disappear and be replaced by a single central "phantom" sound image 230 at the rear of the listener 207. This effect can be mitigated by the use of adaptive de-correlation, which involves derivation of two substantially de-correlated signals from the single monaural channel in order to provide an improved enveloping surround effect.

**[0048]** FIG. 3 is a diagram illustrating 6.1 surround format playback in a 7.1 surround system. In FIG. 3, the speakers labeled 3xx generally correspond to the same speakers labeled 2xx in FIG. 2. When a soundtrack in a 6.1 surround format is played

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on a 7.1 surround system 300 such as shown in FIG. 3, the surround back speakers 324, 325 are fed with identical monaural signals (derived from the single surround back channel in the 6.1 encoding format), which may or may not be delayed with respect to each other to compensate for unequal distances from the optimum listening position.

5 As illustrated in FIG. 3, the identical monaural signals being played through the surround back speakers 324, 325 produces a central "phantom" sound image 330 when the listener is positioned approximately equidistant from them. Reported side effects include "coloration" associated with the phantom sound image 330, which can lead to listener confusion or an unnatural sound, a narrow "sweet spot" (see FIG. 4) due to lack of sound image stability when the listener moves off center from the axis which is equidistant from both surround back speakers 324, 325 (see FIG. 5), and suppression of certain frequency ranges due to cancellations (i.e., nulls) caused by a "comb filter" effect as the sound waves interfere with one another. As a result, the sound quality of a 6.1 surround format soundtrack, when played back in a 7.1 surround system 300, can suffer significantly, particularly for listeners that are not positioned in an optimum listening position.

15 **[0049]** As previously indicated in the Background section hereof, replay of soundtracks in other multi-channel formats (such as Dolby AC-3, DTS or DVD-Audio) can also suffer from similar effects, depending upon the nature of the signals fed to the different left/right and back surround speakers.

20 **[0050]** FIG. 6 is a diagram showing a speaker configuration for a surround sound system 600 in accordance with a preferred embodiment as described herein. The sound system 600 of FIG. 6 includes, similar to the systems 200 and 300 shown in FIGS. 2 and

3, respectively, front left and right speakers 604, 605, a front center speaker 602, a sub-woofer 609, a surround left speaker 614, and a surround right speaker 615. The sound system 600 further includes a surround back left speaker 624 and a surround back right speaker 625, which are preferably positioned in close proximity to one another, possibly even within the same speaker enclosure. The surround back left and right speakers 624, 625 are preferably identical and may be either dipolar or monopolar in nature, but are shown in FIG. 6 as monopolar. The speaker configuration of the sound system 600 illustrated in FIG. 6, coupled with a preferred sound processing technique, can provide improved sound quality when, for example, playing audio tracks recorded in any of the surround sound or multi-channel formats.

**[0051]** When the sound system 600 of FIG. 6 is used to play a soundtrack recorded in 7.1 surround format, the various left, right, center, and surround left/right channel audio signals are fed to the appropriate individual speakers, as would normally be done with a typical 7.1 surround speaker configuration. However, the surround back left and right speakers 624, 625 preferably receive the surround back right channel audio signal and surround back left channel audio signal after sound processing as further described in more detail later herein.

**[0052]** When, on the other hand, the sound system 600 of FIG. 6 is used to play a soundtrack recorded in 6.1 surround format, the various left, right, center, and surround left/right channel audio signals are again fed to the appropriate individual speakers, as would normally be done with a typical 7.1 surround speaker configuration. Typically, assuming that Surround EX playback is properly selected (e.g., a Surround EX flag is present), the surround back left and right speakers 624, 625 both receive and

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respond directly to the surround rear channel audio signal. The central rear sound image produced by the closely spaced surround back left and right speakers 624, 625 from the monaural signal (i.e., the surround rear channel audio signal) is stable over a much wider area, as compared to widely spread surround back left and right speakers, and has significantly less "coloration" or unnaturalness than the audio sound produced by such widely spaced rear surround speakers.

**[0053]** In some instances, such as, for example, where the 6.1 Surround soundtrack is matrix-encoded, or where Surround EX processing is not invoked for whatever reason, a somewhat different type of playback may be experienced. In such a case, the sound system may effectively treat the soundtrack as a 5.1 soundtrack, and may send to the surround back left and right speakers 624, 625 the surround left and right channel audio signals, which may be mixed with at least some portion of the monaural channel information (if the soundtrack is matrix encoded). According to a preferred sound system as disclosed herein, the surround back left and right speakers 624, 625 both receive and respond directly to the surround rear channel audio signal, if such information is present, and, after suitable sound processing, as further described herein, to the surround left/right channel audio signals. FIG. 7 illustrates the playback of a 6.1 surround-encoded soundtrack in the sound system 600 of FIG. 6 in such a situation. As shown in FIG. 7, a wide monaural sound image is projected from the surround back left and right speakers 624, 625. The surround left and right channel audio signals are fed to both the surround left and right speakers 614, 615, and to the surround back left and right speakers 624, 625 after sound processing as further described later herein.

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**[0054]** When the sound system 600 of FIG. 6 is used to play a soundtrack recorded in 5.1 surround format, the various left, right and center channel audio signals are fed to the appropriate individual speakers, as would normally be done with a typical 7.1 surround speaker configuration. Preferred operation with respect to the surround left and right speakers 614, 615 and surround back left and right speakers 624, 625 depends in part upon the nature of the surround left/right channel audio signals. When the surround left/right channel audio signals are monaural in nature, the sound system 600 preferably uses adaptive de-correlation to provide a de-correlated signal for the side surround speakers 614, 615, and provides a direct feed to the surround back left and right speakers 624, 625 to produce a superior rear central image. However, when the surround left/right channel audio signals are stereo in nature, the surround left/right channel audio signals are fed directly to the surround left and right speakers 614, 615 without adaptive de-correlation, and, if desired, after suitable sound processing as further described herein, to the surround back left and right speakers 624, 625. The surround left and right channel audio signals are processed such that the apparent rear sound image size is increased, and its stability is improved at off-axis listening positions. The appropriately apportioned and summed output of the two side surround speakers 614, 615 and the two surround back speakers 624, 625 creates a near-continuous rear-half sound field, thereby improving the sound experience for listeners over a wider area.

**[0055]** FIG. 12 is a simplified diagram conceptually illustrating playback of a 5.1 surround format soundtrack in the sound system 600 of FIG. 6, when the sound system 600 is configured to apply the surround left and right channel audio signals 1211, 1212 to the rear surround speakers 1224, 1125. As illustrated in FIG. 12, when the surround

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left and right channel audio signals 1211, 1212 are monaural, adaptive de-correlation processing (as represented by blocks 1271 and 1272) is activated, and when they are stereo in nature, adaptive sound processing for the rear surround speakers 1224, 1225 (as represented by block 1201) is activated.

5     **[0056]**       More generally, the techniques described herein are capable of producing potentially improved sound for a stereo signal in connection with a speaker configuration that includes two speakers placed in close proximity. Whenever a stereo signal from any encoded program (e.g., surround sound or multi-channel soundtrack), or any audio product or source, is fed directly to the appropriate right and left speakers  
10     (e.g., left and right surround speakers) and, after suitable sound processing as further described herein, to the pair of speakers placed in close proximity (e.g., surround back speakers). The pair of closely spaced speakers is thereby capable of generating a sound image of improved stability and quality over a wider area, thus enlarging the optimum listening area and providing greater satisfaction to the listeners.

15     **[0057]**       Further details regarding preferred sound processing for closely spaced speakers (such as rear surround speakers 624, 625 in FIG. 6) will now be described. FIG. 8 is a generalized block diagram of a sound processing system 800 in accordance with one embodiment as disclosed herein, as may be used, for example, in connection with the speaker configuration illustrated in FIG. 6, or more generally, in any sound  
20     system which utilizes multiple audio channels to provide stereo source signals. As shown in FIG. 8, a left audio signal 811 and right audio signal 812 are provided to a sound processor 810, and then to a pair of closely spaced speakers 824, 825. The left audio signal 811 and right audio signal 812 may also be provided to left and right side

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(surround or non-surround) speakers, not shown in FIG. 8. In a preferred embodiment, the sound processor 810 acts to "spread" the sound image produced by the two closely spaced speakers 824, 825 by employing a cross-cancellation technique wherein a cancellation signal is derived, for example, from the difference between the left and right audio signals 811, 812. The resulting difference signal is scaled, delayed (if necessary) and spectrally modified before being added to the left channel and, in opposite polarity, to the right channel. The spectral modification to the difference channel preferably takes the form of a low-frequency boost over a specified frequency range, in order to restore the correct timbral balance after the differencing process which causes a loss of bass when the low-frequency signals in each channel are similar. The effect of the sound processor 810 is to enlarge the perceived area and stability of the sound image produced by the speakers 324, 325, and provide an effect of stereo sound despite the close proximity of the speakers 324, 325.

**[0058]** FIG. 9-1 is a more detailed diagram of a sound processing system 900 in accordance with various principles as disclosed herein, and as may be used, for example, in connection with the sound system 600 illustrated in FIG. 6, or more generally, in any sound system which utilizes multiple audio channels to provide stereo source signals. In the sound processing system 900 of FIG. 9-1, a left audio signal 911 and right audio signal 912 are provided from an audio source, and may be fed to other speakers as well (not shown in FIG. 9-1). A difference between the left audio signal 911 and right audio signal 912 is obtained by, e.g., a subtractor 940, and the difference signal 941 is fed to a spectral weighting filter 942, which applies a spectral weighting (and possibly a gain factor) to the difference signal 941. The characteristics of the

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spectral weighting filter 942 may vary depending upon a number of factors including the desired aural effect, the spacing of the speakers 924, 925 with respect to one another, the taste of the listener, and so on. The output of the spectral weighting filter 942 may be provided to a phase equalizer 945, which compensates for the phase shifting caused by the spectral weighting filter 942 (if non-linear).

**[0059]** In FIG. 9-1, the output of the phase equalizer 945 is provided to a cross-cancellation circuit 947. The cross-cancellation circuit 947 also receives the left audio signal 911 and right audio signal 912, as adjusted by phase compensation circuits 955 and 956, respectively. The phase compensation circuits 955, 956, which may be embodied as, e.g., all-pass filters, preferably shift the phase of their respective input signals (i.e., left and right audio signals 911, 912) in a complementary manner to the phase shifting performed by the phase equalizer 945 (in combination with the phase distortion caused by the spectral weighting filter 924), such that the phase characteristic of the central channel is substantially 180° degrees out-of-phase with the phase characteristic of the left and right channels over the frequency band of interest. The cross-cancellation circuit 947, which may include a pair of summing circuits (one for each channel), then mixes the spectrally-weighted, phase-equalized difference signal, after adjusting for appropriate polarity, with each of the phase-compensated left audio signal 911 and right audio signal 912. The perceived width of the soundstage produced by the pair of speakers 924, 925 can be adjusted by varying the gain of the difference signal path, and/or by modifying the shape of the spectral weighting filter 942.

**[0060]** FIG. 9-2 is a diagram of a sound processing system 900' in general accordance with the principles and layout illustrated in FIG. 9-1, further showing typical

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examples of possible transfer function characteristics for certain processing blocks. As with FIG. 9-1, in the sound processing system 900' a left audio signal 911' and a right audio signal 912' are provided from an audio source (not shown), and a difference signal 941' is obtained representing the difference between the left audio signal 911' and the right audio signal 912'. The difference signal 941' is fed to a spectral weighting filter 942', which, in the instant example, applies a spectral weighting to the difference signal 941', the characteristics of which are graphically illustrated in the diagram of FIG. 9-2. A more detailed graph of the transfer function characteristics (both gain and phase) of the spectral weighting filter 942' in this example appears in FIG. 15-1. As shown therein, the spectral weighting filter 942' is embodied as a first-order shelf filter with a gain of 0 dB at low frequencies, and turn-over frequencies at approximately 200 Hz and 2000 Hz. If desired, the gain applied by gain/ amplifier block 946' can be integrated with the spectral weighting filter 942', or the gain can be applied downstream as illustrated in FIG. 9-2. In any event, as previously noted, the turnover frequencies, amount of gain, slope, and other transfer function characteristics may vary depending upon the desired application and/or overall system characteristics.

**[0061]** A phase equalizer 945' is provided in the center processing channel, and addition phase compensation circuits 955' and 956' in the right and left channels, to ensure that the desired phase relationship is maintained, over the band of interest, between the center channel and the right and left channels. As shown graphically in both FIG. 9-2 and in more detail in FIG. 15-1, the spectral weighting filter 942' in the instant example causes a phase distortion over at least the 200 Hz to 2000 Hz range. The phase equalizer 945' provides no gain, but modifies the overall frequency

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characteristic of the center channel. The phase compensation circuits 955' and 956' likewise modify the phase characteristics of the left and right channels, respectively. The phase compensation is preferably selected, in the instant example, such that the phase characteristic of the center channel (that is, the combined phase effect of the spectral weighting filter 942' and the phase equalizer 945') is approximately 180° out-of-phase with the phase characteristic of the left and right channels, over the frequency band of interest (in this example, over the 200 Hz to 2000 Hz frequency band). At the same time, the phase characteristic of the left and right channels are preferably remains the same, so that, among other things, monaural signals being played over the left and right channels will have identical phase processing on both channels (and thus maintain proper sound characteristics). Therefore, the phase compensation circuits 955' and 956' preferably are configured to apply identical phase processing to the left and right channels.

**[0062]** More detailed graphical examples of gain and phase transfer functions (with the gain being zero in this case when the components are embodied as all-pass filters) are illustrated for the center channel phase equalizer 945' in FIG. 15-2 and for the left and right channel phase compensation circuits 955', 956' in FIG. 15-3. In these examples, the phase equalizer 945' is embodied as a second-order all-pass filter (with  $F = 125$  Hz and  $Q = 0.12$ ), and the phase compensators 955', 956' are each embodied as second-order all-pass filters (with  $F = 3200$  Hz and  $Q = 0.12$ ). A higher  $Q$  value may be used to increase the steepness of the phase drop-off, reducing the extent to which the center channel is out-of-phase with the left and right channels at low frequencies (thus minimizing the burden imposed upon the speakers 924', 925').

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**[0063]** FIG. 11 illustrates another implementation of the sound system 900 shown in FIG. 9-1, where all-pass filters 1157, 1158 are used in phase compensation blocks 1155 and 1156, respectively, to provide phase equalization and/or compensation. In FIG. 11, elements labeled with reference numerals "11xx" generally correspond to their counterparts labeled "9xx" in FIG. 9-1.

**[0064]** FIG. 10 is another diagram of a sound processing system 1000, in accordance with the general principles explained with respect to FIGS. 3 and 9, illustrating representative transfer functions according to an exemplary embodiment as described herein. In the sound processing system 1000 shown in FIG. 10, input audio signals X1 and X2 (e.g., left and right audio signals) are processed along two parallel paths, and the resultants individually summed together and provided as output signals Y1 and Y2, respectively (which may be fed to a pair of speakers, e.g., left and right speakers located in close proximity). A difference between the input audio signals X1 and X2 is obtained from a subtractor 1040, which provides the resulting difference signal 1040 to a processing block 1060 having a transfer function  $-B$ . The first input audio signal X1 is also fed to a processing block 1055 having a transfer function  $A$ , and the output of processing block 1055 is added together with the output of processing block 1060 and fed as the first output signal Y1. Likewise, the second input audio signal X2 is fed to a processing block 1056 having a transfer function  $-A$  (i.e., the inverse of the transfer function  $A$  of processing block 1055), and the output of processing block 1056 is inverted and added together with the inverted output of processing block 1060, then fed as the second output signal Y2. The overall relationship between the inputs and the outputs of the FIG. 10 sound processing system 1000 can be expressed as:

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$$A \left( \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + B \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix} \right) \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

In a preferred embodiment, the transfer function  $-B$  of processing block 1060 represents  
 5 the combined transfer functions of a spectral weighting filter of desired characteristics  
 and a phase equalizer, such as illustrated by the difference path in the sound processing  
 system 400 of FIG. 4. Also in a preferred embodiment, the transfer functions  $A$  and  $-A$   
 of processing blocks 1055 and 1056, respectively, each represent the transfer function  
 of a phase compensation network that performs a complementary phase shifting to  
 10 compensate for the phase effects caused by the processing block 1060. The polarities in  
 FIG. 10 are selected so that appropriate cross-cancellation will be attained.

**[0065]** In a preferred embodiment, input signals  $X_1$  and  $X_2$  represent the Z-  
 transforms of the left and right audio channel inputs, and  $Y_1$  and  $Y_2$  represent the  
 corresponding Z-transforms of the left and right channel outputs which feed the pair of  
 15 speakers (e.g., left and right speakers) located in close proximity. The transfer functions  
 $A$ ,  $-A$ , and  $B$  may be represented in terms of  $z$ , and are determined in part by the  
 sampling frequency  $F_s$  associated with processing in the digital domain. According to a  
 particular embodiment, blocks 1055 and 1056 are each second-order all-pass filters with  
 $f = 3200$  Hertz,  $Q = 0.12$ , and may, in one example, possess the following transfer  
 20 function characteristics based upon representative examples of the sampling frequency  
 $F_s$ :

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**[0066]** For  $F_s = 48$  KHz,

$$A(z) = \frac{-0.2578123 - 0.6780222z^{-1} + z^{-2}}{1 - 0.6780222z^{-1} - 0.2578123z^{-2}}$$

**[0067]** For  $F_s = 44.1$  KHz,

$$A(z) = \frac{-0.2944196 - 0.633509z^{-1} + z^{-2}}{1 - 0.633509z^{-1} - 0.2944196z^{-2}}$$

**[0068]** For  $F_s = 32$  KHz,

$$A(z) = \frac{-0.4201395 - 0.469117z^{-1} + z^{-2}}{1 - 0.469117z^{-1} - 0.4201395z^{-2}}$$

In this particular embodiment, block 1060 may be a first-order shelf having a gain of 0 dB at low frequencies and turn-over frequencies of 200 Hertz and 2 KHz in cascade with a second-order all pass filter, with  $f = 125$  Hz,  $Q = 0.12$ , and may, in one example, possess the following transfer function characteristics based upon representative examples of the sampling frequency  $F_s$ :

**[0069]** For  $F_s = 48$  KHz,

$$B(z) = G \times \frac{0.1116288 - 0.0857871z^{-1}}{1 - 0.9741583z^{-1}} \times \frac{0.8723543 - 1.872104z^{-1} + z^{-2}}{1 - 1.872104z^{-1} + 0.8723543z^{-2}}$$

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**[0070]** For  $F_s = 44.1$  KHz,

$$B(z) = G \times \frac{0.1126427 - 0.0845478z^{-1}}{1 - 0.9719051z^{-1}} \times \frac{0.8618468 - 1.861552z^{-1} + z^{-2}}{1 - 1.861552z^{-1} + 0.8618468z^{-2}}$$

5 **[0071]** For  $F_s = 32$  KHz,

$$B(z) = G \times \frac{0.1173312 - 0.0788175z^{-1}}{1 - 0.9614863z^{-1}} \times \frac{0.814462 - 1.813915z^{-1} + z^{-2}}{1 - 1.813915z^{-1} + 0.814462z^{-2}}$$

A gain factor may also be included in block 1060, or else may be provided in the same  
 10 path but as a different block or element. The gain may be determined for a particular application by experimentation, but is generally expected to be optimal in the range of 10-15 dB. In one embodiment, for example, the gain factor is 12 dB.

**[0072]** FIGS. 13 and 14 are graphs illustrating examples of frequency response and phase transfer functions for a sound processing system in accordance with FIG. 10  
 15 and having particular spectral weighting, equalization and phase compensation characteristics. FIG. 13 illustrates a frequency response transfer function 1302 and phase transfer function 1305 for  $-B/A$ , which represents the transfer function of the difference channel ( $-B$ ) and the first input channel (X1) with +12 dB of gain added. As shown in FIG. 13, the frequency response transfer function 1302 exhibits a relatively flat  
 20 gain in a first region 1320 of bass frequencies (in this example, up to about 200 Hertz), a decreasing gain in a second region 1321 of mid-range frequencies (in this example, from about 200 Hertz to about 2 KHz), and then a relatively flat gain again in a third region

1322 of high frequencies (in this example, above 2 KHz). The phase response transfer function 1305 indicates that in the second region 1321 of mid-range frequencies (i.e., between about 200 Hertz and 2 KHz) the output signal remains substantially in phase.

**[0073]** FIG. 14 illustrates a frequency response transfer function 1402 and phase transfer function 1405 for  $-B/-A$ , which represents the transfer function of the difference channel ( $-B$ ) and the first input channel (X2) with +12 dB of gain added. In FIG. 14, as with FIG. 13, the frequency response transfer function 1402 exhibits a relatively flat gain in a first region 1420 of bass frequencies (in this example, up to about 200 Hertz), a decreasing gain in a second region 1421 of mid-range frequencies (in this example, from about 200 Hertz to about 2 KHz), and then a relatively flat gain again in a third region 1422 of high frequencies (in this example, above 2 KHz). The phase response transfer function 1405 indicates that in the second region 1421 of mid-range frequencies (i.e., between about 200 Hertz and 2 KHz) the output signal is substantially inverted in phase (i.e., at 180 degrees).

**[0074]** As noted, the output signals Y1, Y2 are preferably provided to a pair of speakers located in close proximity. The transfer functions **A**,  $-A$ , and **B** are examples selected for the situation where the speakers are located substantially adjacent to one another. However, benefits may be attained in the system 1000 of FIG. 10, or other embodiments described herein, where the pair of speakers are not immediately adjacent, but are nevertheless in close proximity with one another.

**[0075]** FIG. 16 is a diagram of a sound processing system 1600 in accordance with an alternative embodiment as described herein, employing a linear spectral weighting filter. In the sound processing system 1600 of FIG. 16, a left audio signal

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1611 and right audio signal 1612 are processed to derive a pair of processed audio signals 1648, 1649 which are applied to a pair of closely spaced speakers 1624, 1625 (e.g., left and right speakers). The left and right audio signals 1611, 1612 are operated upon by a subtractor 1640, which outputs a difference signal 1641 representing a  
5 difference between the left and right audio signals 1611, 1612. The difference signal 1641 is fed to a spectral weighting filter 1642 having a linear phase characteristic. The spectral weighting filter 1642 may have frequency response characteristics in general accordance, for example, with the transfer function illustrated in FIG. 7A or 7B. Because the spectral weighting filter 1642 has a linear phase characteristic, phase  
10 equalization and compensation are not necessary. Therefore, the output of the spectral weighting filter 1642 may be provided directly to a cross-cancellation circuit 1646, which then mixes the spectrally weighted signal with each of the left and right audio channels before applying them to the speakers 1624, 1625. To compensate for the delay caused by the spectral weighting filter 1642, delay components 1655 and 1656  
15 may be added along the left and right channel paths, respectively. The delay components 1655, 1656 preferably have a delay characteristic equal to the latency of the linear spectral weighting filter 1642.

**[0076]** The amount of cross-cancellation provided by the sound processing in various embodiments generally determines the amount of “spread” of the sound image.

20 If too much cross-cancellation is applied, then the resulting sound can seem clanky or echoey. If, on the other hand, too little cross-cancellation is applied, then the sound image may not be sufficiently widened or stabilized.

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**[0077]** The pair of speakers (e.g., speakers 824 and 825 in FIG. 8, or closely spaced speakers in other embodiments described herein) which receive the sound processed information are preferably located immediately adjacent to one another; however, they may also be physically separated while still providing benefits of enlarged sound image, increased stability, and so on. Generally, the maximum acceptable separation of the pair of speakers can be determined by experimentation, but performance may gradually decline as the speakers are moved farther apart from one another. Preferably, the two speakers are placed no further apart than a distance that is comparable with the wavelength of the highest frequency that is intended to be radiated by the speakers. For a maximum frequency of 2 kHz, this separation would correspond to a center-to-center spacing of about 6 inches between the two speakers. However, ideally the two speakers are placed immediately next to one another, in order to attain the maximum benefit from the sound processing techniques as described herein.

**[0078]** Certain embodiments of the invention may find application in a variety of contexts other than home theater or surround sound systems. For example, implementations of the invention may, in some circumstances, be applicable to personal computer systems (e.g., configured to play audio tracks, multi-media presentations, or video games with "three-dimensional" or multi-channel sound), automobile or vehicular audio systems, portable stereos, televisions, radios, and any other context in which sound reproduction is desired. Certain embodiments may find particular utility in situations in which possible speaker locations are limited and/or the maximum spacing between left and right speakers is severely limited, but where two adjacent or closely spaced speakers could be achieved. For example, the pair of closely spaced left and

right speakers may be part of an integrated portable stereo unit, or else may be located atop or beneath a computer monitor, etc.

**[0079]** Automobile or vehicular audio systems, in particular, may benefit from application of the inventive concepts disclosed herein. Audio systems are commonplace in automobiles and certain other vehicles. Such systems generally utilize program sources ranging from simple radios to relatively elaborate stereo or multi-channel systems with CD and cassette players together with multiple equalizers, pre-amplifiers, power amplifiers etc.

**[0080]** While there is a great variety in the configuration and components of conventional automotive audio systems, most of them suffer to varying degrees from a number of persistent problems in providing the highest sound quality. These problems partially result from the unique sound environment of the automobile when compared with a good listening room. Among the disadvantages are:

- Much smaller internal volume resulting in a reduced reverberation time and lower modal density at low frequencies resulting in a lack of ambience and an uneven bass response .
- The proximity of highly reflective surfaces (such as the windows) to highly absorbtive areas such as the upholstery or the occupants clothing leads to a great variability with frequency and head position of the direct to indirect sound arriving at the listener. Consequently even small changes in head or seating position can cause significant and undesirable changes in the timbral quality of the music.

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- The listening positions are necessarily restricted to the seating positions provided (usually 4 or 5) and all of these are very asymmetrically placed with respect to the speaker positions. Space is always at a premium within a car interior and as a result the speakers are often placed in physically convenient positions, that are nevertheless very poor from an acoustic point of view, such as the foot wells and the bottom of the front and rear side doors. As a result the listener's head is always much closer to either the left or right speaker leading directly large inter-channel time differences and different sound levels due to the  $1/r$  law.
- Additionally, the angles between the axes from the listeners ears to the axes of symmetry of the left and right speakers is quite different for each occupant. The perceived spectral balance is different for each channel due to the directional characteristics of the drive units. Masking of one or more speakers by the occupants clothes or legs can often result in the attenuation of the mid- and high- frequencies by as much as 10dB.

All of the above adversely impact the ability to produce high quality stereo reproduction, which ideally has the following attributes:

- A believable and stable image or soundstage resulting from the listener being nearly equidistant from the speakers reproducing the left and right channels and a sufficiently high ratio of direct-to-indirect sound at the listener's ears .
- A smooth timbral balance at all the listening positions .

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- A sense of ambience resulting from a uniform soundfield.

[0081] Some features are provided in automobile audio systems which can partially mitigate the aforementioned problems. For example, an occupant can manually adjust the sound balance to increase the proportional volume to the left or right speakers. Some automobile audio systems have a "driver mode" button which makes the sound optimal for the driver. However, because different listening axes exist for left and right occupants, an adjustment to the balance that satisfies the occupant (e.g., driver) on one side of the automobile will usually make the sound worse for the occupant seated on the other side of the automobile. Moreover, balance adjustment requires manual adjustment by one of the occupants, and it is generally desirable in an automobile to minimize user intervention.

[0082] Another modification made to some automobile audio systems is to provide a center speaker, which reduces the image instability that occurs when the listener is closer to either the left or right speaker when both are reproducing the same mono signal, with the intention of producing a central sound image. Other potential approaches which might be taken in an attempt to mitigate the foregoing automotive sound problems include adding more speakers in a greater variety of positions (e.g., at the seat tops). While such techniques can sometimes provide a more pleasing effect, they cannot provide stable imaging as the problems associated with asymmetry described above still remain. The considerable additional cost of such design approaches is usually undesirable in the highly cost sensitive and competitive

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automotive industry. Moreover, as previously noted, space is usually at a premium in the automobile interior, and optimal speaker positions are limited.

**[0083]** According to one or more embodiments as disclosed herein which are designed to overcome one or more of the foregoing problems, drawbacks, or disadvantages, a preferred automobile sound reproduction system comprises a pair of speakers placed close together and located in the front of the console or dashboard with their geometric center on (or as near as possible to) the central axis of symmetry of the vehicle. The sound reproduction system further preferably comprises a sound processor which provides audio signals to the pair of speakers. Because the left and right center speakers are effectively adjacent to one another, the difference in time of arrival of the sound information becomes minimal, and the relative volume level of both speakers remains approximately the same. Moreover, both the right and left occupant experience approximately the same volume level from the center pair of speakers and the ratio of direct to indirect sound is minimized.

**[0084]** According to a preferred embodiment, the sound processor acts to "spread" the sound image produced by the two closely spaced speakers by employing a cross-cancellation technique in which, for example, the cancellation signal is derived from the difference between the left and right channels. The resulting difference signal is scaled, delayed (if necessary) and spectrally modified before being added to the left channel and, in opposite polarity, to the right channel. The spectral modification to the difference channel preferably takes the form of a low-frequency boost over a specified frequency range, in order to restore the correct timbral balance after the differencing process which causes a loss of bass when the low-frequency signals in each channel are

similar. Additional phase-compensating all-pass networks may be inserted in the difference channel to correct for the extra phase shift contributed by the usually minimum-phase-shift spectral modifying circuit so that the correct phase relationship between the canceling signal and the direct signal is maintained over the desired frequency range.

**[0085]** Alternatively, a linear-phase network may be employed to provide the spectral modification to the difference channel, in which case compensation can be provided by application of an appropriate, and substantially identical, frequency-independent delay to both left and right channels.

**[0086]** In various embodiments, the pair of central speakers may be placed in a common enclosure with a central dividing partition that is inserted into or else integral with the front console or dashboard of the automobile. In certain embodiments, the center speakers may be placed with their diaphragms facing down and in close proximity to a rigid reflecting surface such that substantially all of the sound energy is directed forward, towards the listener, via an arrow slot in the enclosure. The resultant radiating system provides the dual benefit of occupying less dashboard area, where space is always at a premium, and possessing a very wide directional characteristics due to the slot having dimensions that can be made very small with respect to the wavelength the radiated sound.

**[0087]** The use of a pair of central speakers in conjunction with sound processing to provide improved sound quality may be employed in more than one location in the automobile, to extend the foregoing concepts further. Thus, for example, a pair of rear central speakers with similar sound processing may be added in the rear of the vehicle,

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for example in the center above the rear seatback, for use in the play back of program with discretely encoded or simulated multi-channel surround sound. Likewise, for larger vehicles (e.g., a limousine), a pair of front central speakers may be used in both the driver compartment and the passenger compartment, the latter having applications for rear seat video presentations of films or music videos having multi-channel surround sound.

**[0088]** FIG. 17 is a diagram of a preferred automobile sound system 1700 in accordance with one or more embodiments as disclosed herein. In FIG. 17, two speakers 1714, 1715 are positioned in close proximity to one another, and receive and respond to audio signals 1732 and 1733, respectively, from a sound processor 1708. The speakers 1714, 1715 are preferably left and right speakers, may (but need not) be nominally identical, may be separated by a distance  $\Delta D$  from one another as further described herein, and may be of any suitable size and type provided that they fit within the size constraints of the available automotive compartment(s) or other space. Further, the speakers 1714, 1715 may be positioned along or near the central axis of the interior of the automobile, such as, for example, in the center console, or atop the center of the dashboard, or in a central island between the driver and passenger seats.

**[0089]** The sound processor 1708 receives audio input signals 1702 and 1703 from a suitable audio signal source 1705, from any typical automotive audio components (e.g., CD player, cassette player, radio, etc.) that may be included therewith. The audio input signals 1702, 1703 may be derived from any audio product, including any prerecorded medium (such as a cassette, CD, or DVD), any digital audio file, or any wireless (e.g., radio) broadcast received by the audio system. The sound

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processor 1708 preferably processes the stereo sound signals 1702, 1703 according to techniques described in more detail herein, and provides the processed signals 1732, 1733 (after any desired amplification or level shifting) to the pair of closely spaced speakers 1714, 1715. The stereo signals 1702, 1703 may also optionally be fed, either  
5 directly or via the sound processor 1718 (if certain additional or complementary sound processing is desired) to additional speakers, if any, such as left speaker 1724 and right speaker 1725 shown in FIG. 17.

**[0090]** In a preferred embodiment, the sound processor 1708 acts to effectively “spread” the sound image by, in a broad sense, taking the difference between the two  
10 audio channels 1702, 1703, spectrally modifying the intermediate difference signal, and then, after scaling, adding it in appropriate polarity to the left and right channels. When the speakers 1714, 1715 are placed close together, side-by-side, the resulting phenomenon causes an apparent expansion of the stereo sound image despite the fact that the speakers 1714, 1715 are located in close proximity.

**[0091]** The bass lifting or spectral weighting carried out by the sound processor 1708 may cause phase shifting, which can be compensated for using phase equalization. Complementary phase compensation can be provided along each of the  
15 audio channels 1702, 1703 prior to mixing (i.e., cross-cancellation) so that the left and right audio channels 1702, 1703 are substantially in phase with the spectrally modified  
20 difference signal. Where the bass lifting or spectral weighting is accomplished using linear phase filtering, however, no phase equalization may be needed or desired, although equal delays are preferably added to both the left and right audio channel paths in order to compensate for the additional delay produced by the linear-phase

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equalizer in the difference channel. The primary purpose of the speakers 1714, 1715 is not necessarily to provide only monaural information, as with a conventional centrally positioned speaker (although monaural information may be fed to the speakers 1714, 1715), but rather, when combined with suitable mid- to high-frequency processing and mixing (via the sound processor 1708), to produce a symmetrical spreading of stereo information, which results in a better stereo presentation for both left and right occupants regardless of the listening axis.

[0092] Because the two center speakers 1714, 1715 are closely spaced with respect to one another, the difference in time of arrival of the sound information to a given listener becomes minimal, and the relative volume level of both speakers, as perceived by a given listener, is approximately the same. Moreover, both the right and left occupant will generally experience approximately the same volume level from the center pair of speakers 1714, 1715. In the event that the closely spaced speakers are unable to radiate potentially large out-of-phase, low-frequency components resulting from the cross-cancellation process, the very low frequencies can be isolated by means of a low-pass filter and directed to a separate sub-woofer, while a corresponding high-pass filter may be utilized to prevent high-level, low-frequency signals from overloading the smaller speakers. For any bass audio components that might be difficult for the relatively small center speakers 1714, 1715 to handle, the left and right audio channels 1702, 1703 can be fed to left and right bass speakers 1721 and 1722, respectively, possibly in conjunction with attenuation at mid/high frequencies and/or boosting at low/bass frequencies as provided by the sound processor 1708 or any other suitable means. In embodiments in which mid/high frequencies are output by the center pair of

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closely spaced speakers and bass or low frequencies are output by left and right door-mounted speakers, advantages in amplifier efficiency may be achieved because less power will generally be needed to obtain higher volume levels.

**[0093]** When the speakers 1714, 1715 are placed in the front console or dashboard, or otherwise on or near the center axis of the automobile, they may (but need not be) mounted at a sufficient height so as to have a relatively unobstructed pathway to the listeners' ears, thus eliminating muffling or damping associated with obstructions such as seats and occupant bodies. In such embodiments, the speakers 1714, 1715 are located at an ideal or at least preferably acoustical position, being less obstructed and less reflected, and allowing more space for the sound to unfold.

**[0094]** The pair of speakers (e.g., speakers 1714 and 1715 in FIG. 17) which receive the sound processed information are preferably located immediately adjacent to one another; however, they may also be separated by some distance  $\Delta b$  while still providing benefits of enlarged sound image, increased stability, and so on. Generally, the farthest maximum separation of the speakers 1714, 1715 can be determined by experimentation, but performance may gradually decline as the speakers 1714, 1715 are moved farther apart from one another. Preferably, the pair of speakers 1714, 1715 are placed no further apart than a distance that is comparable with the wavelength of the highest frequency that is intended to be radiated by the speakers 1714, 1715. For a maximum frequency of 2 kHz, this would correspond to a center-to-center spacing of about 6 inches between speakers 1714 and 1715. However, ideally the speakers 1714, 1715 are placed immediately next to one another, in order to attain the maximum benefit from the sound processing techniques as described herein.

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**[0095]** When the pair of speakers 1714, 1715 are closely spaced, they may be placed in a common enclosure, with a central (preferably airtight) dividing partition, that may, for example, may be inserted into or else integral with the front console or dashboard of an automobile, or placed elsewhere near the central axis of the automobile. FIGS. 20-1, 20-2, and 20-3 illustrate one example of an enclosure 2001, particularly suited to applications where space is limited, housing a pair of speakers 2014, 2015 which can receive and respond to sound processed signals from left and right audio channels in accordance with the various techniques described herein. FIG. 20-1 is a front cut-away view of the exemplary speaker enclosure 2001 housing the pair of speakers 2014, 2015; FIG. 20-2 is a top cross-sectional view of the speaker enclosure 2001 shown in FIG. 20-1; and FIG. 20-3 is an oblique front view of the speaker enclosure 2001 shown in FIGS. 20-1 and 20-2. As shown perhaps best in FIG. 20-3, the speaker enclosure 2001 in this example is preferably substantially rectangular in shape, and is preferably designed with dimensions so as to slide into or otherwise fit within a standard "DIN " slot (approximately 8" by 2 ½") in the front console space of an automobile. The speaker enclosure 2001 may include a front panel 2032, a pair of side panels 2030, a top panel 2035, a bottom panel 2039, and possibly a back panel 2031. To achieve isolation between the two speakers 2014, 2015, an interior wall 2016 such as illustrated in FIG. 20-1 and 20-2 may be placed between the speakers 2014, 2015, thus creating two separate speaker chambers, one housing each of the two speakers 2014, 2015.

**[0096]** The pair of speakers 2014, 2015 may be pointed directly frontwards; however, in the instant example, the speakers 2014, 2015 are oriented downwards, as

illustrated in FIG. 20-1. When so oriented, a slot 2019 may be located at the bottom of the speaker enclosure 2001, to allow the sound from the speakers 2014, 2015 to radiate outwards towards the direction of the listeners in the automobile. Effectively, then, the speakers 2014, 2015 only take up an amount of surface space corresponding to the size of the slot 2019. In an automobile environment, front console/dash space is typically extremely valuable since it is scarce, and thus the ability to position two speakers 2014, 2015 in the front console/dash while minimizing the amount of surface space consumed can be extremely advantageous. Audio system controls/display(s) or other conventional console accouterments (controls, LCD or other displays, air vents, etc.) can be attached to or integral with the front panel 2032 of the speaker enclosure 2001, so the available surface space on the front panel 2032 is valuably utilized.

**[0097]** Moreover, when so oriented, the speakers 2014, 2015 may be potentially larger in size (assuming console space is limited); for example, each speaker may be about 4" (for a total of 8" across collectively), which fits into the 8" DIN space, whereas the speakers would otherwise generally have to be under 2 ½" to fit within the DIN space, if oriented in a frontwards direction. The ability to place larger speakers in the center speaker unit allows better bass reproduction and, hence, reduces or potentially dispenses with the need for side (e.g., door-mounted) bass speakers to carry the bass information of the left and right channels.

**[0098]** The effect of orienting the speakers 2014, 2015 in a downward direction is conceptually illustrated in FIG. 20-4, which shows a generic speaker 2090 pointing downwards towards a surface 2091. The sound output from the speaker 2090 radiates outward from the centerpoint along the surface 2091 in essentially all directions (i.e., a

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complete 360-degree circle). Thus, as shown in FIGS. 20-1 and 20-3, a slot 2019 is preferably located at the bottom of the speaker enclosure 2001, to allow the sound from the speakers 2014, 2015 to radiate outwards towards the direction of the listeners in the automobile. A layer of insulation 2012 (e.g., foam) preferably matching the outer contours of the speakers 2014, 2015, as illustrated in FIG. 20-2, may be placed within the speaker enclosure 2001, so that the sound does not reflect on the back panel 2031 (if any) of the speaker enclosure. In the resulting speaker enclosure configuration, sound emanating from the speakers 2014, 2015 is cleanly projected through the slot 2019 to the listeners in the automobile.

**[0099]** In an alternative embodiment, the speakers 2014, 2015 might be directed upwards instead of downwards, with the slot 2019 being located at the top of the speaker enclosure 2001, to achieve a similar effect. The speakers 2014, 2015 may alternatively be positioned sideways, either facing towards or away from each other, with a pair of slots (one for each of the speakers 2014, 2015) being vertical in orientation rather than horizontal, as with slot 2019. In such an embodiment, the speaker enclosure may be taller but narrower in size.

**[0100]** In some circumstances, high frequencies (such as over 2 KHz) might become lost or reduced in the speaker enclosure configuration illustrated in FIGS. 20-1 through 20-3. Therefore, one or more additional speakers 2017 of small size (e.g., tweeters) may be advantageously placed above the "bell" of the speakers 2014, 2015 and in the front panel 2032 of the speaker enclosure 2001, to radiate the higher frequencies.

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**[0101]** While the speaker enclosure 2001 shown in FIGS. 20-1 through 20-3 has certain advantages for placement in a standard DIN space of an automobile, it should be understood that the closely spaced speakers 1714, 1715, whether or not contained in a speaker enclosure 2001, may be positioned in other areas of the automobile as well, such as atop the front dashboard, above the rear seatback, or in a center console or island located between the front seats or between the front and back seats. Preferably, the closely spaced speakers 1714, 1715 are located on or near the center axis of the automobile, so as to provide optimal sound quality evenly to occupants on both sides.

**[0102]** Because of space constraints within an automobile, the centrally located speakers (e.g., speakers 1714, 1715 in FIG. 17) may be of limited size. Smaller speakers, however, tend to suffer losses at low frequencies. To compensate for the loss of low frequency components where the central pair of speakers are small, left and right bass speakers (e.g., speakers 1724, 1725) may be provided in a suitable location – for example, built into the automobile doors. The left and right audio channels fed to the left and right door speakers can be processed to attenuate the mid/high frequencies and/or boost the bass audio components,. Providing bass frequencies through the door speakers will not destroy the stereo effect of the mid/high frequencies provided by the central pair of speakers, since it is well known that frequencies below about 100 Hz are not normally localized by the human listener.

**[0103]** In addition, as previously noted, a sub-woofer may be added in a suitable location within the automobile to further enhance very low frequency bass audio components. The sub-woofer may be located, for example, in the rear console of the car above the rear seatback, or in any other suitable location.

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**[0104]** In certain situations, passengers in the back seat area of the automobile may actually experience even better sound quality than the front occupants, because they are farther away from the stereo source (that is, the pair of central front speakers). Various modifications may be made to provide even further improved sound for the front occupants as well. For example, a similar pair of closely spaced speakers to those placed in the front console or area can also be placed in the rear of the automobile, for example, atop the rear seatback on or in the rear parcel shelf. The same signals that are used to feed the front pair of closely spaced speakers can be used to feed the rear pair of closely spaced speakers. If desired, a speaker enclosure 2001, such as shown in FIGS. 20A – 20C, containing the pair of closely spaced speakers may be placed in the rear of the vehicle to house these rear speakers.

**[0105]** FIG. 19-1 is a simplified top view of an automobile 1900 illustrating an example of placement of a pair of closely spaced speakers 1905 (whether or not in a speaker enclosure) in the front section of the automobile 1900 (e.g., in the front console or the front dash), with the addition of two door-mounted speakers 1907, 1908 for, e.g., providing added bass or low frequency audio components. FIG. 19-2 illustrates an example similar to FIG. 19-1, but adding a pair of closely spaced speakers 1930 (whether or not in a speaker enclosure) in the rear of the automobile 1920. FIG. 19-3 illustrates an example of placement of speakers in a large vehicle such a limousine, with separate driver and passenger compartments. In the driver compartment 1941, the layout is similar to FIG. 19-1, with a pair of closely spaced speakers 1945 in the front area (e.g., console, dash, or the like) of the vehicle 1940, and pair of door-mounted left and right speakers 1947, 1948. In the passenger compartment 1942, the layout is

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similar to FIG. 19-2, with two pairs of closely spaced speakers 1955, 1960, one in the front area and one in the rear area of the passenger compartment 1942, with a pair of right and left door-mounted speakers 1957, 1958 also. Of course, in any of these examples, any number of additional speakers and audio components may be added based upon individual need and preference, subject to spatial limitations of the vehicle, cost, etc.

**[0106]** In certain applications, it may be desirable to provide surround sound or other multi-channel capability in a vehicular automotive system, in conjunction with the closely spaced speaker arrangement described previously herein. For example, a van or other large vehicle may have a DVD system which allows digital audio-visual media to be presented to the passengers of the vehicle, with the sound potentially being played through the vehicle audio system. In other cases, it may be desirable to allow for extreme right and left directional sound, which may originate by the existence of left and right surround channels on the recorded medium, or simply by the presence of an extreme and intentional disparity in the relative volumes of the left and right channel.

**[0107]** A block diagram illustrating an example of an automobile sound system 2100 for providing potentially improved extreme right/left sound, in connection with the pair of closely spaced center speakers 2114, 2115, is illustrated in FIG. 21. The system 2100 shown therein operates much as described with the FIG. 17 sound system 1700 with respect to the closely spaced center speakers 2114, 2115, producing the illusion of a widened stereo sound image for the occupants of the vehicle. In addition, the sound system 2100 illustrates the feed of left and right audio signals 2102, 2103 to left and right door-mounted speakers 2124, 2125, optionally through low pass filters 2181,

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2182, respectively, to emphasize the bass tones. To produce extreme left/right sounds, which may be difficult with the closely spaced speakers 2114, 2115, some portion (dictated by a gain factor  $k$ ) of the difference between the left and right audio channels 2102, 2103 is mixed in to each of the signals fed into the left and right door mounted speakers 2124, 2125. When the left and right audio channels 2102, 2103 are close in amplitude (and frequency), the signals mixed into the left and right channels fed to the door mounted speakers 2124, 2125 are negligible. However, as the difference between the left and right audio channels 2102, 2103 grows, the signal fed into the left or right channel (depending on which channel is larger) grows proportionately (in a linear or non-linear fashion, depending upon preference). A large difference between the left and right audio channels 2102, 2103 indicates an extreme left or right sound, which, in the sound system 2100 of FIG. 21, can be successfully reproduced in the left or right door-mounted speakers 2124, 2125.

**[0108]** Another embodiment, directed to a surround or multi-channel sound system 1800 as may be utilized in a vehicle, is illustrated in block form in FIG. 18. As shown therein, the sound system 1800 may include an audio signal source 1805 which provides a source for left and right audio channels 1802, 1803, which are fed to a sound processor 1808 which functions in a manner similar to sound processor 1708 shown in FIG. 17, or various other sound processor embodiments described herein with respect to closely spaced left/right central speakers. The left and right audio signals 1802, 1803 may, in the present example, comprise front left and front right audio signals of a surround sound formatted medium. A center audio signal of the surround sound formatted medium may be mixed into the signals 1832, 1833 provided to the closely

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spaced speakers 1814, 1815, and may also be provided to additional center speakers 1817 (e.g., tweeters), if provided. The closely spaced speakers 1814, 1815 and additional speakers 1817 may be embodied and arranged, for example, in the form of the speaker enclosure and arrangement illustrated in FIGS. 20A – 20C. A surround left and surround right audio channel 1871, 1872 may be fed into surround left and right speakers 1824, 1825, which may be dipolar or monopolar in nature. The surround left and right speakers 1824, 1825 may be generally used to provide ambient sound. When the surround left and right audio channels 1871, 1872 are monaural in nature, adaptive decorrelation may be employed, as well understood in the art, to prevent signal cancellation or similar sound deterioration.

**[0109]** Left and right speakers 1834, 1835, which may be, e.g., door-mounted speakers, may be directly fed the left and right audio channels 1802, 1803, or else may be fed only the bass/low frequency tones, possibly mixed with extreme right or left sound components, such as described previously with respect to the sound system of FIG. 21.

**[0110]** In addition, the sound system 1800 of FIG. 18 may further be provided with an additional pair of closely spaced speakers (not shown) located at the rear of the vehicle. The additional pair of closely spaced speakers may be fed the same processed left and right audio channel signals 1832, 1833 as provided to the front closely spaced speakers 1814, 1815, or may be fed similarly processed signals derived from the surround left and right audio channel signals 1871, 1872, or alternatively, surround back left and back right audio channel signals (not shown), if the audio product is encoded in a 7.1 surround or similar multi-channel format.

**[0111]** FIG. 23 is a diagram of a surround or multi-channel sound system 2300 similar to the sound system 1800 shown in FIG. 18, but illustrating the presence of a pair (right and left) of closely spaced surround back speakers 2394, 2395. In the embodiment shown in FIG. 23, a rear surround processor 2398 receives as inputs two surround back channels 2392, 2393 provided from the audio signal source 2305. The rear surround processor 2398 preferably provides sound processing to the two surround back channels 2392, 2393 for the closely spaced rear surround speakers 2394, 2395 in a manner similar to that for the closely spaced front right/ left speakers 2314, 2315, using any of the sound processing techniques described herein for closely spaced speakers. The sound processing for the surround back speakers 2394, 2395 need not be identical to that of the closely spaced front right/left speakers 2314, 2315, but may differ in terms of spectral weighting, gain, etc., to account for the fact that the surround back speakers 2314, 2315 may serve a different purpose to some degree than the front right/left speakers 2314, 2315.

**[0112]** The content of the surround back channels 2392, 2393 may depend upon the format of the encoded audio product. In 5.1 surround format, for example, the surround back channels 2392, 2393 may be the same as the right and left surround channels 2371, 2372. In 6.1 surround format, the surround back channels 2392, 2393 may be the same as the right and left surround channels 2371, 2372, added or mixed with the single surround back channel. In 7.1 surround format, the surround back channels 2392, 2393 are preferably the independent left and right surround back channels encoded in the audio product.

**[0113]** In various embodiments as described herein, improved sound quality results from a stereo sound image that has stability over a larger area than would otherwise be experienced with, e.g., speakers spaced far apart without comparable sound processing. Consequently, the audio product (e.g., soundtrack) can be enjoyed  
5 with optimal or improved sound over a larger area, and by more listeners who are able to experience improved sound quality even when positioned elsewhere than the center of the speaker arrangement. Thus, for example, a home theater surround sound system or automobile sound system may be capable of providing quality sound to a greater number of listeners, not all of whom need to be positioned in the center of the speaker  
10 arrangement in order to enjoy the playback of the particular audio product.

**[0114]** In any of the foregoing embodiments, the audio product from which the various audio source signals are derived, before distribution to the various speakers or other system components, may comprise any audio work of any nature, such as, for example, a musical piece, a soundtrack to an audio-visual work (such as a DVD or other  
15 digitally recorded medium), or any other source or content having an audio component. The audio product may be read from a recorded medium, such as a DVD, cassette, compact disc, CD-ROM, or else may be received wirelessly, in any available format, from a broadcast or point-to-point transmission. The audio product preferably has at least left channel and right channel information (whether or not encoded), but may also  
20 include additional channels and may, for example, be encoded in a surround sound or other multi-channel format, such as Dolby-AC3, DTS, DVD-Audio, etc. The audio product may also comprise digital files stored, temporarily or permanently, in any format

used for audio playback, such as, for example, an MP3 format or a digital multi-media format.

**[0115]** The various embodiments described herein can be implemented using either digital or analog techniques, or any combination thereof. The term "circuit" as used herein is meant broadly to encompass analog components, discrete digital components, microprocessor-based or digital signal processing (DSP), or any combination thereof. The invention is not to be limited by the particular manner in which the operations of the various sound processing embodiments are carried out.

**[0116]** While examples have been provided herein of certain preferred or exemplary filter characteristics, transfer functions, and so on, it will be understood that the particular characteristics of any of the system components may vary depending on the particular implementation, speaker type, relative speaker spacing, environmental conditions, and other such factors. Therefore, any specific characteristics provided herein are meant to be illustrative and not limiting. Moreover, certain components, such as the spectral weighting filter described herein with respect to various embodiments, may be programmable so as to allow tailoring to suit individual sound taste.

**[0117]** The spectral weighting filter in the various embodiments described herein may provide spectral weighting over a band smaller or larger than the 200 Hertz to 2 KHz band. If the selected frequency band for spectral weighting is too large, then saturation may occur or clipping may result, while if the selected frequency band is too small, then the spreading effect may be inadequate. Also, if cross-cancellation is not mitigated at higher frequencies, as it is in the spectral weighting filters illustrated in

certain embodiments herein, then a comb filter effect might result which will cause nulls at certain frequencies. Therefore, the spectral weighting frequency band, and the particular spectral weighting shape, is preferably selected to take account of the physical limitations of the speakers and electronic components, as well as the overall quality and effect of the speaker output.

**[0118]** While certain system components are described as being “connected” to one another, it should be understood that such language encompasses any type of communication or transference of data, whether or not the components are actually physically connected to one another, or else whether intervening elements are present.

It will be understood that various additional circuit or system components may be added without departing from teachings provided herein.

**[0119]** In some embodiments, the pair of closely spaced speakers may be forced to work harder than they would without cross-cancellation, because the cross-mixing of left and right signals requires that the speakers reproduce out-of-phase sound waves. To compensate for this effect, it may, for example, be desirable in some embodiments to increase the size of the amplifier(s) feeding the audio signals to the pair of closely spaced speakers. In any of the embodiments described herein, the speakers utilized in the automobile sound system may be passive or active (i.e., with built-in or on-board amplification capability) in nature. The various audio channels may be individually amplified, level-shifted, boosted, or otherwise conditioned appropriately for each individual speaker or pair of speakers.

**[0120]** While preferred embodiments of the invention have been described herein, many variations are possible which remain within the concept and scope of the

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invention. Such variations would become clear to one of ordinary skill in the art after inspection of the specification and the drawings. The invention therefore is not to be restricted except within the spirit and scope of any appended claims.

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## CLAIMS

What is claimed is:

1. A sound system, comprising:

5 a left speaker and a right speaker located in close proximity;

a left channel audio signal;

a right channel audio signal; and

a sound processor receiving as inputs said left channel audio signal and said right  
channel audio signal, said sound processor configured to cross-cancel a spectrally  
10 weighted stereo difference signal with said left channel audio signal and said right  
channel audio signal prior to applying said left channel audio signal and said right  
channel audio signal to said left speaker and said right speaker, respectively.

2. The sound system of claim 1, wherein said sound processor is configured  
15 to generate a difference signal representing a difference between said left channel audio  
signal and said right channel audio signal, and to apply a spectral weighting to said  
difference signal thereby generating said spectrally weighted signal.

3. The sound system of claim 2, wherein said sound processor comprises a  
20 subtractor for generating said difference signal.

4. The sound system of claim 2 or 3, wherein said sound processor  
comprises a spectral weighting filter for applying said spectral weighting to said

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difference signal, said spectral weighting filter being characterized by a first filter region of relatively level gain, a second filter region having a generally decreasing gain with increasing frequency, and a third filter region of relatively level gain.

5           5.     The sound system of claim 4, wherein said spectral weighting filter is further characterized by a roll-off from said first filter region to said second filter region at approximately 200 Hertz.

10           6.     The sound system of claim 5, wherein said spectral weighting filter is further characterized by a boundary between said second filter region and said third filter region at approximately 2 KHz.

            7.     The sound system of claim 2, 3, 4, 5 or 6, wherein said sound processor comprises a linear filter for applying the spectral weighting to said difference signal.

15           8.     The sound system of any of the preceding claims, wherein said sound processor further comprises a phase equalizer for equalizing the phase of said spectrally weighted difference signal prior to cross-cancellation, and a plurality of phase compensators, having a phase characteristic complementary to said phase equalizer and  
20     said spectral weighting filter over a frequency band of desired cross-cancellation, placed in series along each of said left channel audio signal and right channel audio signal, respectively, prior to cross-cancellation.

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9. The sound system of claim 8, wherein said phase equalizer comprises a plurality of all pass filters collectively having a first phase transfer function, and wherein each of said phase compensators comprises a plurality of all pass filters collectively having a second phase transfer function complementary to a combined phase characteristic of said phase equalizer and said spectral weighting filter over a frequency band of desired cross-cancellation.

10. The sound system of claim 8, wherein said phase equalizer comprises a second order filter.

11. The sound system of any of the preceding claims, wherein said left channel audio signal comprises a surround left channel audio signal coupled to a surround left speaker, wherein said right channel audio signal comprises a surround right channel audio signal which is coupled to a surround right speaker, and wherein said left speaker and said right speaker comprise a surround back left speaker and a surround back right speaker, respectively, for utilization in a surround sound stereo system.

12. The sound system of any of the preceding claims, wherein said sound processor is implemented in whole or in part in the digital domain.

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13. The sound system of any of the preceding claims, wherein said left speaker and said right speaker are positioned within a distance corresponding to a wavelength of a highest frequency intended to be radiated by the left and right speakers

5 14. The sound system of any of the preceding claims, wherein said left speaker and said right speaker are immediately adjacent.

15. The sound system of claim 1, wherein said sound processor comprises:  
a subtractor receiving as inputs said left channel audio signal and right channel  
10 audio signal, and outputting a difference signal representing a difference between said left channel audio signal and said right channel audio signal;

a spectral weighting filter receiving said difference signal as an input and outputting a spectrally weighted signal; and

a cross-cancellation circuit for mixing said spectrally weighted signal with said  
15 left channel audio signal and said right channel audio signal, thereby generating a first speaker signal for said left speaker and a second speaker signal for said right speaker.

16. The sound system of claim 15, wherein said spectral weighting filter is characterized by a first filter region of relatively level gain, a second filter region having  
20 a generally decreasing gain with increasing frequency, and a third filter region of relatively level gain.

17. The sound system of claim 15 or 16, further comprising a phase equalizer interposed between said spectral weighting filter and said cross-cancellation circuit.

18. The sound system of claim 17, further comprising a first phase  
5 compensator interposed between said left channel audio signal and said cross-cancellation circuit, said first phase compensator having a phase characteristic complementary to a combined phase characteristic of said phase equalizer and said spectral weighting filter, and a second phase compensator interposed between said right  
10 channel audio signal and said cross-cancellation circuit, said second phase compensator having a phase characteristic complementary to said combined phase characteristic.

19. The sound system of claim 18, wherein said phase equalizer comprises a plurality of all pass filters, and wherein said first phase compensator and said second phase compensator each comprises a plurality of all pass filters having a substantially  
15 identical phase transfer function.

20. The sound system of claim 17, wherein said phase equalizer comprises a second order filter.

20 21. The sound system of any of the preceding claims, wherein said left speaker and said right speaker are located in a vehicle.

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22. The sound system of claim 21, wherein said left speaker and said right speaker are positioned substantially on or near a center axis of the vehicle.

23. The sound system of claim 21 or 22, wherein said left speaker and said  
5 right speaker are mounted within a common housing.

24. The sound system of claim 23, wherein said right speaker and left speaker are oriented in a downwards or upwards direction towards a flat surface of said common housing, and wherein said common housing defines at least one slot near an edge of  
10 said flat surface allowing sound to emanate from said left speaker and said right speaker without obstruction from an interior of said common housing.

25. The sound system of claim 24, further comprising an insulating material residing within said common housing and opposite said slot, said insulating material  
15 generally conforming to outer contours of said left speaker and right speaker.

26. The sound system of claim 23, 24 or 25, further comprising one or more additional speakers mounted in or on said common housing, said one or more additional speakers oriented directly towards the interior of the vehicle.

20 27. The sound system of claims 21, 22, 23, 24, 25, or 26, further comprising a pair of door-mounted left and right speakers.

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28. A method for adaptively reproducing sound in a manner so as to enlarge the perceived area and stability of a stereo sound image, the method comprising the steps of:

placing a left speaker and a right speaker in close proximity;

5 receiving a left channel audio signal;

receiving a right channel audio signal; and

cross-canceling a spectrally weighted stereo difference signal with said left channel audio signal and said right channel audio signal prior to applying said left channel audio signal and said right channel audio signal to said left speaker and said right speaker, respectively, said spectrally weighted difference signal derived from said left channel audio signal and said right channel audio signal.

29. The method of claim 29, wherein said spectrally weighted difference signal is generated by obtaining a difference signal representing a difference between said left channel audio signal and said right channel audio signal, and applying said difference signal to a spectral weighting filter.

30. The method of claim 29, wherein said spectral weighting filter is characterized by a first filter region of relatively level gain, a second filter region having a generally decreasing gain with increasing frequency, and a third filter region of relatively level gain.

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31. The method of claim 30, wherein said spectral weighting filter is further characterized by a roll-off from said first filter region to said second filter region at approximately 200 Hertz.

5 32. The method of claim 31, wherein said spectral weighting filter is further characterized by a boundary between said second filter region and said third filter region at approximately 2 KHz.

10 33. The method of claim 29, 30, 31, or 32, further comprising the step of performing phase equalization on an output of said spectral weighting filter prior to said step of cross-canceling said bass-enhanced stereo difference signal with said left channel audio signal and said right channel audio signal.

15 34. The method of claim 33, further comprising the step of performing phase compensation on each of said left channel audio signal and right channel audio signal to compensate for said step of performing phase equalization on said output of said spectral weighting filter.

20 35. The method of claim 34, wherein said step of performing phase equalization on said output of said spectral weighting filter is carried out using a first plurality of all pass filters, and wherein said step of performing phase compensation on each of said left channel audio signal and right channel audio signal is carried out using a second and third plurality of all pass filters

36. The method of claim 34, wherein said step of performing phase equalization is carried out using a second order filter.

5 37. The method of claim 29, wherein said spectral weighting filter comprises a linear filter.

38. The method of any of preceding claims 28 through 37, wherein said left channel audio signal comprises a surround left channel audio signal which is coupled to  
10 a surround left speaker, wherein said right channel audio signal comprises a surround right channel audio signal which is also fed to a surround right speaker, and wherein said left speaker and said right speaker comprise a surround back left speaker and a surround back right speaker, respectively, for utilization in a surround sound stereo system.

15 39. The method of any of preceding claims 28 through 38, wherein said step of placing left speaker and said right speaker in close proximity comprises the step of placing said left speaker and said right speaker within a distance corresponding to a wavelength of a highest frequency intended to be radiated by the left and right speakers

20 40. The method of any of preceding claims 28 through 39, wherein said left speaker and said right speaker are immediately adjacent.

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41. The method of claim 28, wherein said step of cross-canceling said spectrally weighted stereo difference signal with said left channel audio signal and said right channel audio signal comprises the steps of:

generating a difference signal representing a difference between said left channel  
5 audio signal and said right channel audio signal;

applying a spectral weighting to said difference signal thereby generating a spectrally weighted signal; and

cross-canceling said spectrally weighted signal with said left channel audio signal and said right channel audio signal, thereby generating a first speaker signal for said left  
10 speaker and a second speaker signal for said right speaker.

42. The method of claim 41, wherein said step of generating said difference signal is carried out using a subtractor.

15 43. The method of claim 41 or 42, wherein said step of applying said spectral weighting to said difference signal is carried out using a spectral weighting filter, said spectral weighting filter being characterized by a first filter region of relatively level gain, a second filter region having a generally decreasing gain with increasing frequency, and a third filter region of relatively level gain.

20 44. The method of claim 41, 42 or 43, further comprising the steps of:

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performing phase equalization on said difference signal prior to said step of cross-canceling said spectrally weighted signal with said left channel audio signal and said right channel audio signal; and

performing phase compensation on each of said left channel audio signal and  
5 right channel audio signal to compensate for the spectral weighting and phase equalization performed on said difference signal.

45. The method of claim 44, wherein said step of performing phase equalization on said difference signal is carried out using a first plurality of all pass filters  
10 collectively having a first phase transfer function, and wherein said step of performing phase compensation on each of said left channel audio signal and right channel audio signal is carried out using a second and third plurality of all pass filters, said second plurality of all pass filters and said third plurality of all pass filters each having a collective phase transfer function complementary to a combined phase transfer function  
15 of said first phase transfer function and a spectral weighting phase transfer function associated with the step of applying spectral weighting to said difference signal.

46. The method of claim 44, wherein said step of performing phase equalization is carried out using a second order filter.

20

47. The method of any of preceding claims 41 through 46, wherein said step of applying said spectral weighting to said difference signal is carried out using a linear filter.

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48. The method of any of the preceding claims 41 through 46, wherein one or more of said steps of generating said difference signal, applying a spectral weighting to said difference signal, and cross-canceling said spectrally weighted signal with said left  
5 channel audio signal and said right channel audio signal is carried out in whole or in part in the digital domain.

49. The method of any of preceding claims 28 through 48, further comprising the step of placing said left speaker and said right speaker in a vehicle.

10

50. The method of claim 49, further comprising the step of positioning said left speaker and said right speaker substantially on or near a center axis of the vehicle.

51. The method of claim 49 or 50, further comprising the step of mounting  
15 said left speaker and said right speaker within a common housing.

52. The method of claim 51, wherein said right speaker and left speaker are oriented in a downwards or upwards direction towards a flat surface of said common housing, and wherein said common housing defines at least one slot near an edge of  
20 said flat surface allowing sound to emanate from said left speaker and said right speaker without obstruction from an interior of said common housing.

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53. The method of claim 52, wherein an insulating material resides within said common housing and opposite said slot, said insulating material generally conforming to outer contours of said left speaker and right speaker.

5 54. The method of claim 51, 52 or 53, further comprising the step of mounting one or more additional speakers in or on said common housing, said one or more additional speakers oriented directly towards the interior of the vehicle.

10 55. The method of claims 50, 51, 52, 53, or 54, further comprising a pair of door-mounted left and right speakers.

56. A sound reproduction system for a surround sound stereophonic system, comprising:

15 a surround left speaker;  
a surround right speaker;  
a pair of surround back speakers located in close proximity;  
a surround left channel audio signal electrically connected to said surround left speaker;  
a surround right channel audio signal electrically connected to said surround  
20 right speaker; and

a sound processor receiving as inputs said left channel audio signal and said right channel audio signal, said sound processor configured to generate a difference signal representing a difference between said surround left channel audio signal and said

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surround right channel audio signal, apply a spectral weighting to said difference signal thereby generating a spectrally weighted signal, and cross-cancel said spectrally weighted signal with said surround left channel audio signal and said surround right channel audio signal, thereby generating a first speaker signal and a second speaker  
5 signal for said pair of surround back speakers.

57. The sound reproduction system of claim 56, wherein said pair of surround back speakers comprises a surround left back speaker and a surround right back speaker.

10 58. The sound reproduction system of claim 56, wherein said pair of surround back speakers are located in a single speaker enclosure.

59. The sound reproduction system of claim 56, further comprising a left speaker, a right speaker, and a center speaker.

15 60. The sound reproduction system of claim 56, further comprising a first adaptive decorrelation circuit interposed between said surround left channel audio signal and said surround left speaker, and a second adaptive decorrelation circuit interposed between said surround right channel audio signal and said surround right  
20 speaker.

61. The sound reproduction system of claim 56, wherein said sound processor comprises a spectral weighting filter for applying said spectral weighting to said

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difference signal, said spectral weighting filter being characterized by a first filter region of relatively level gain, a second filter region having a generally decreasing gain with increasing frequency, and a third filter region of relatively level gain.

5           62.    The sound reproduction system of claim 61, wherein said spectral weighting filter is further characterized by a roll-off from said first filter region to said second filter region at approximately 200 Hertz.

10           63.    The sound reproduction system of claim 62, wherein said spectral weighting filter is further characterized by a boundary between said second filter region and said third filter region at approximately 2 KHz.

15           64.    The sound reproduction system of claim 56, wherein said sound processor further comprises a phase equalizer for equalizing the phase of said difference signal prior to cross-cancellation, and a plurality of phase compensators complementary in phase characteristics to a combined phase characteristic of said phase equalizer and said spectral weighting filter, said phase compensators placed in series along each of said surround left channel audio signal and surround right channel audio signal, respectively, prior to cross-cancellation.

20

          65.    The sound reproduction system of claim 64, wherein said phase equalizer comprises a plurality of all pass filters, and wherein each of said phase compensators comprises a plurality of all pass filters.

-66-

66. The sound reproduction system of claim 56, wherein said sound processor comprises a linear filter for applying the spectral weighting to said difference signal.

5           67. The sound reproduction system of claim 56, wherein said surround left speaker and said surround right speaker are each dipole speakers.

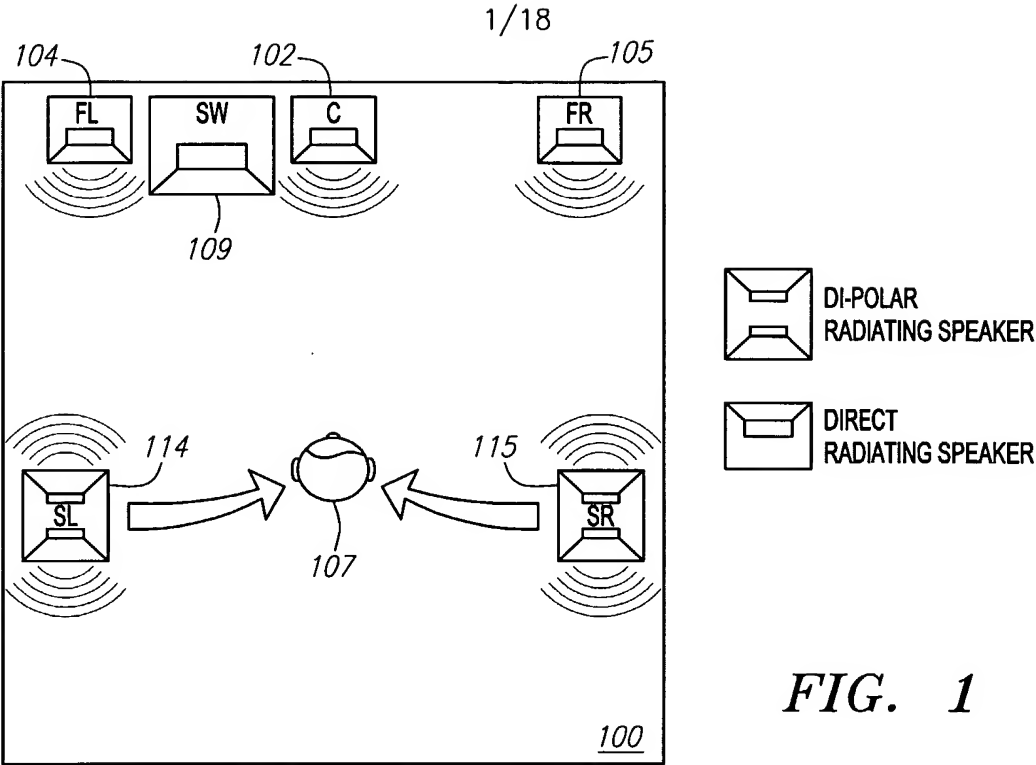


FIG. 1

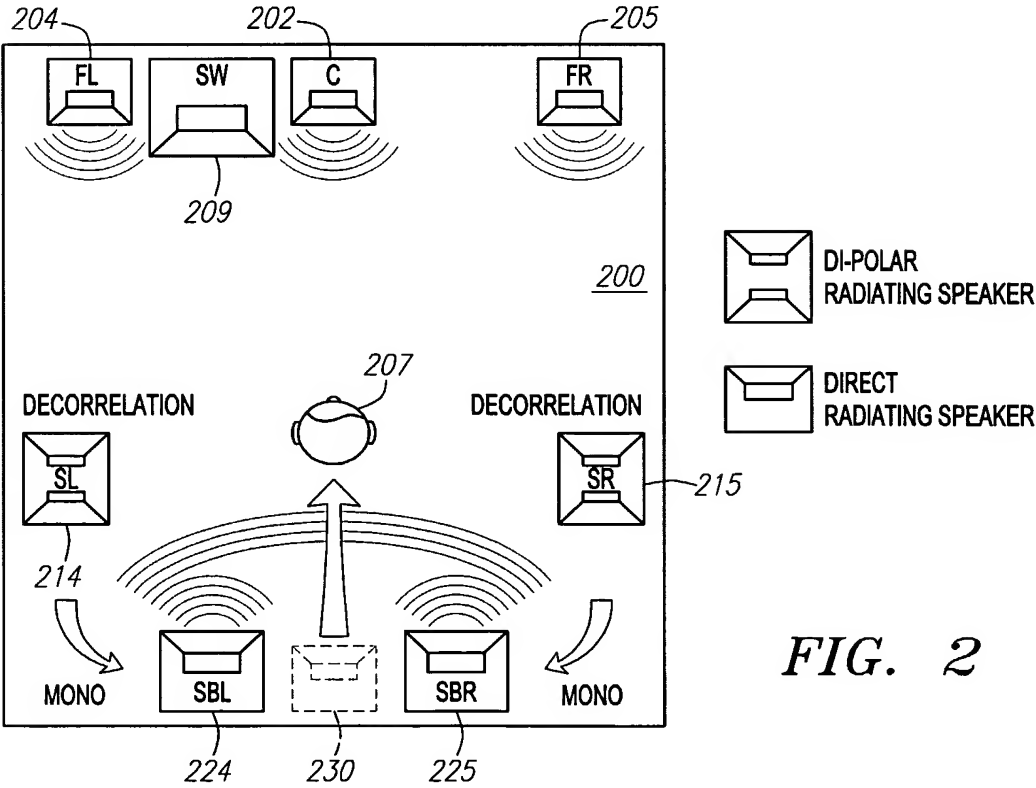


FIG. 2

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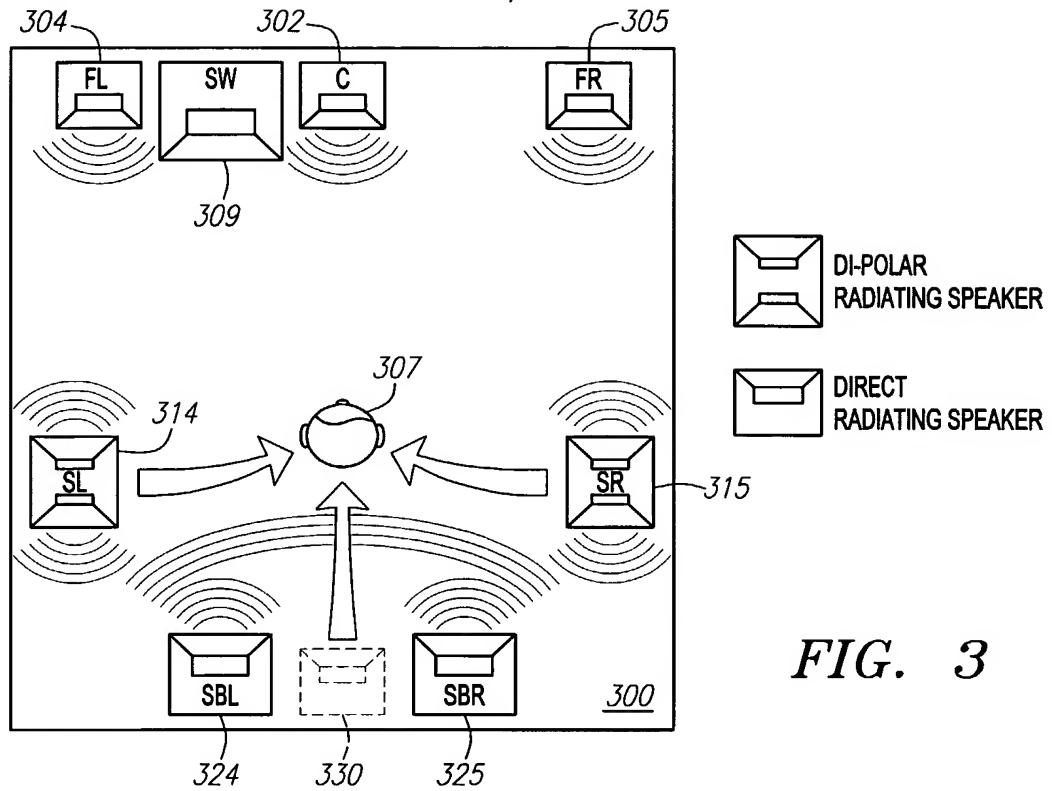


FIG. 3

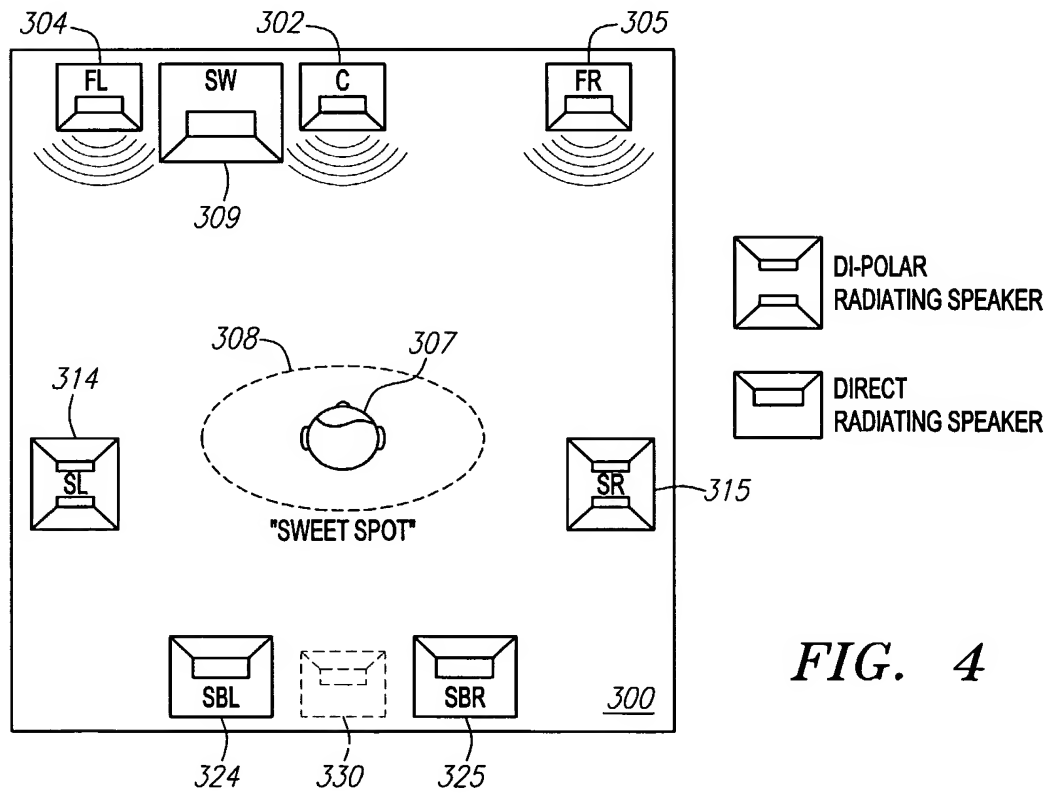
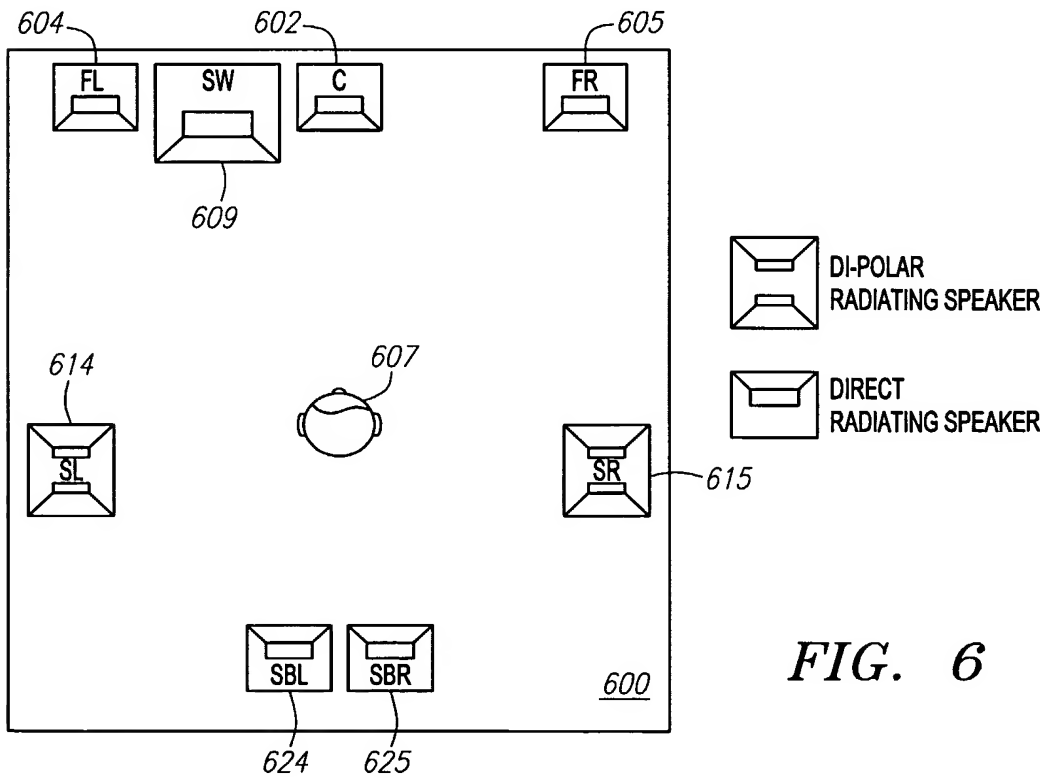
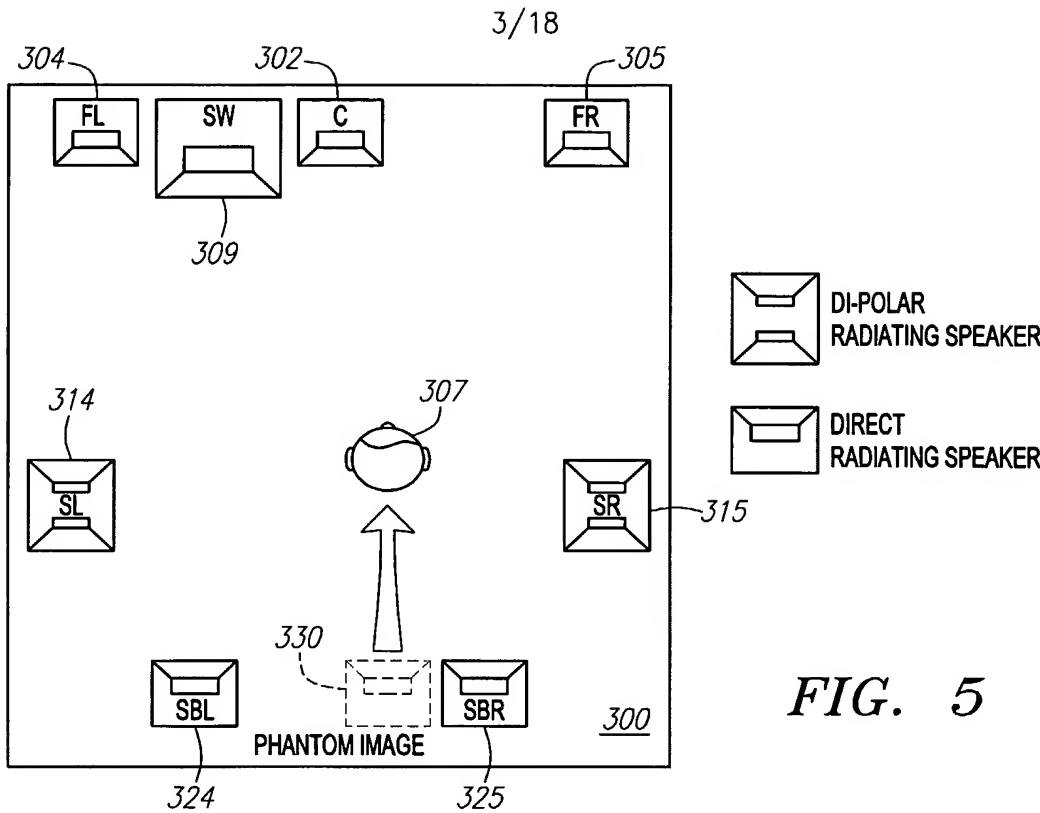
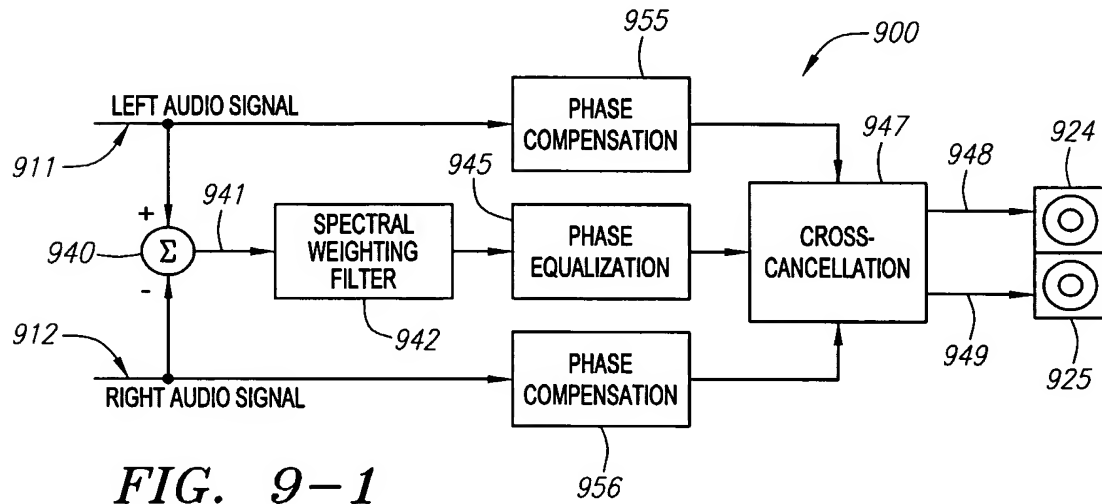
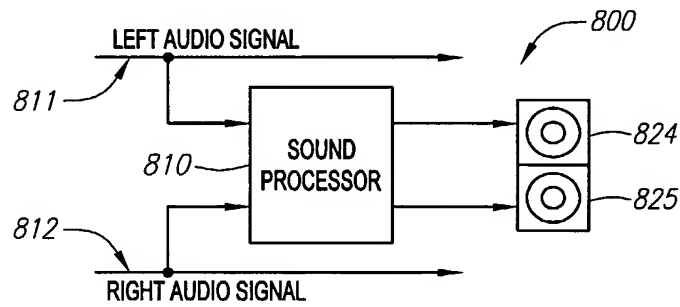
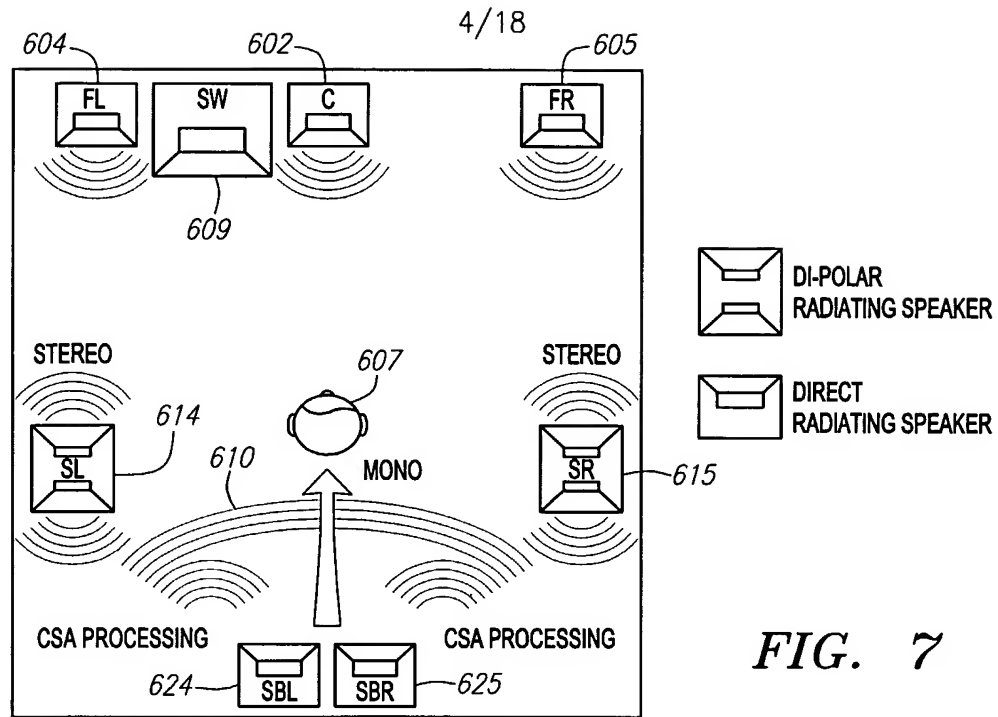


FIG. 4





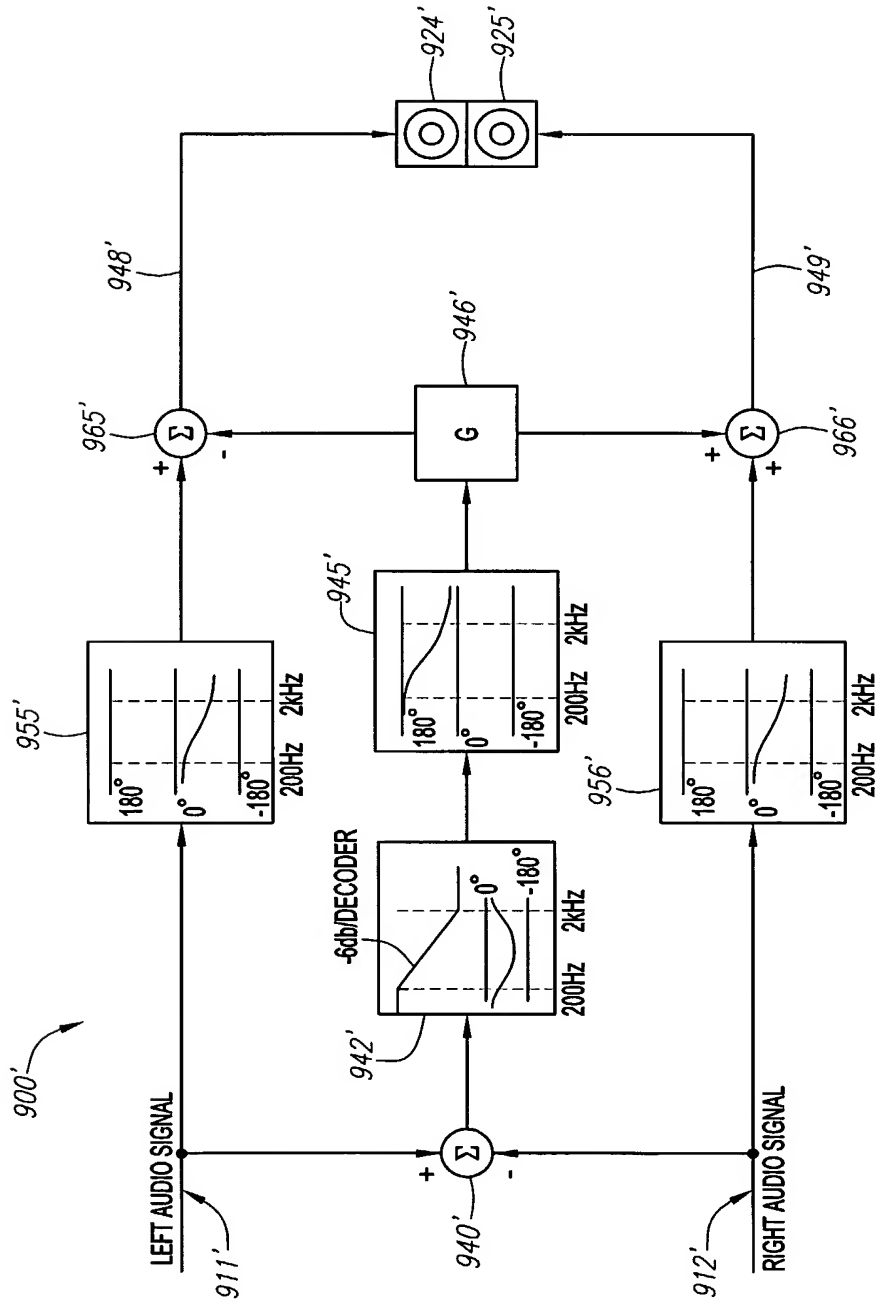
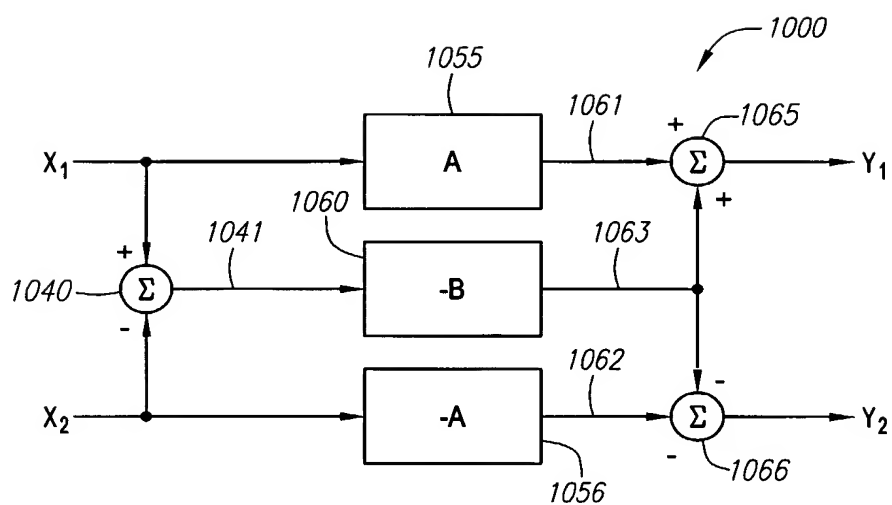


FIG. 9-2

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*FIG. 10*

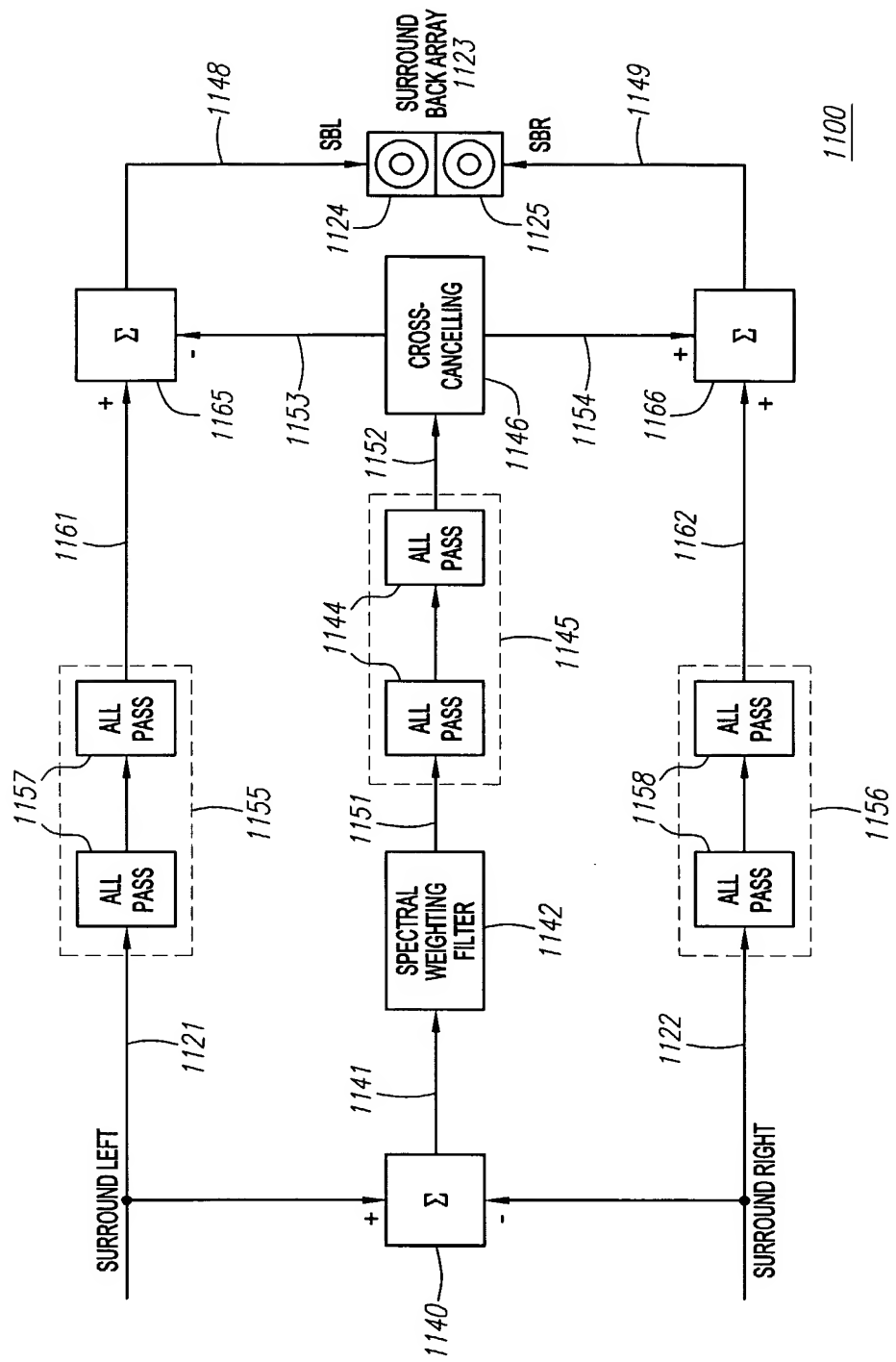


FIG. 11

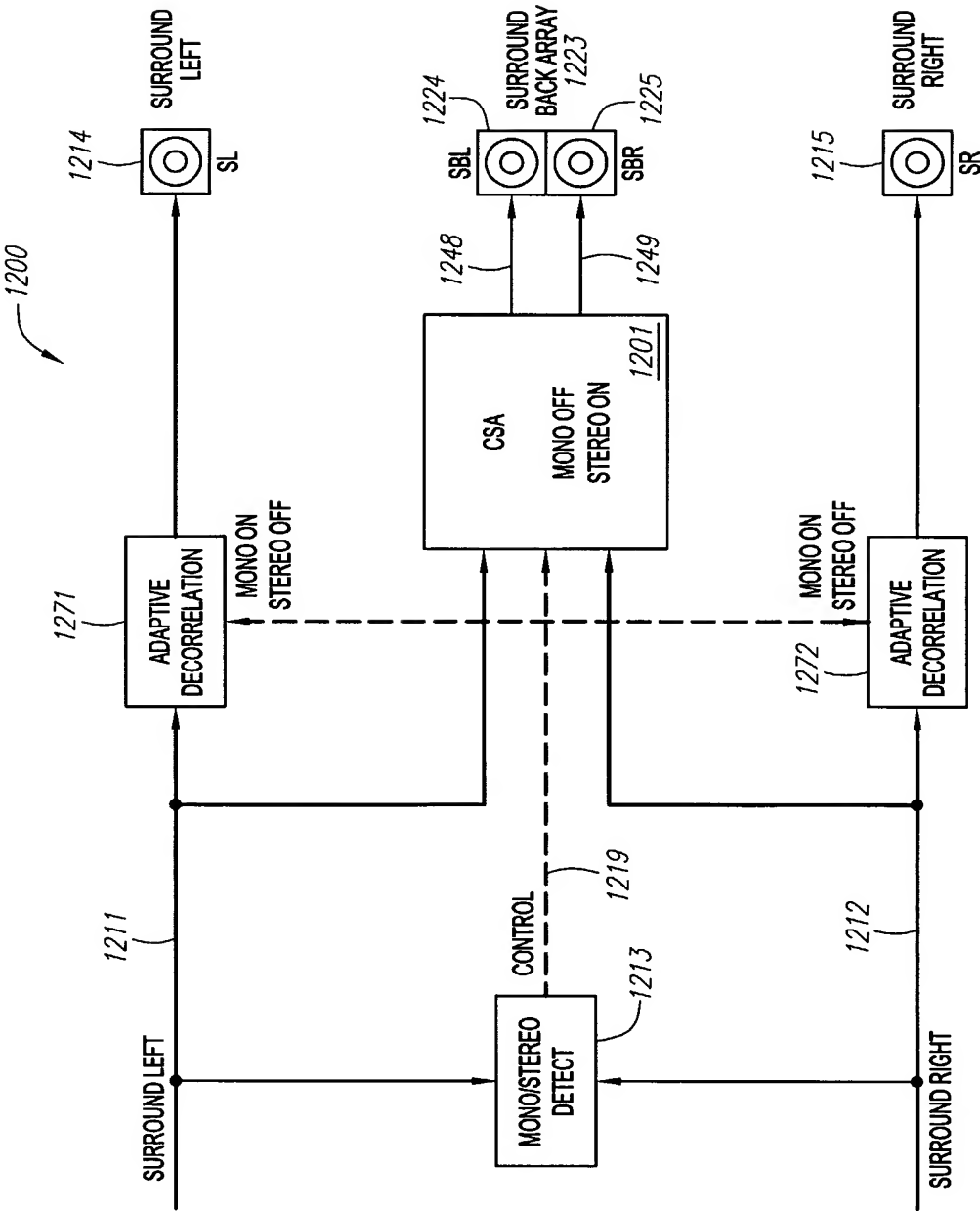


FIG. 12

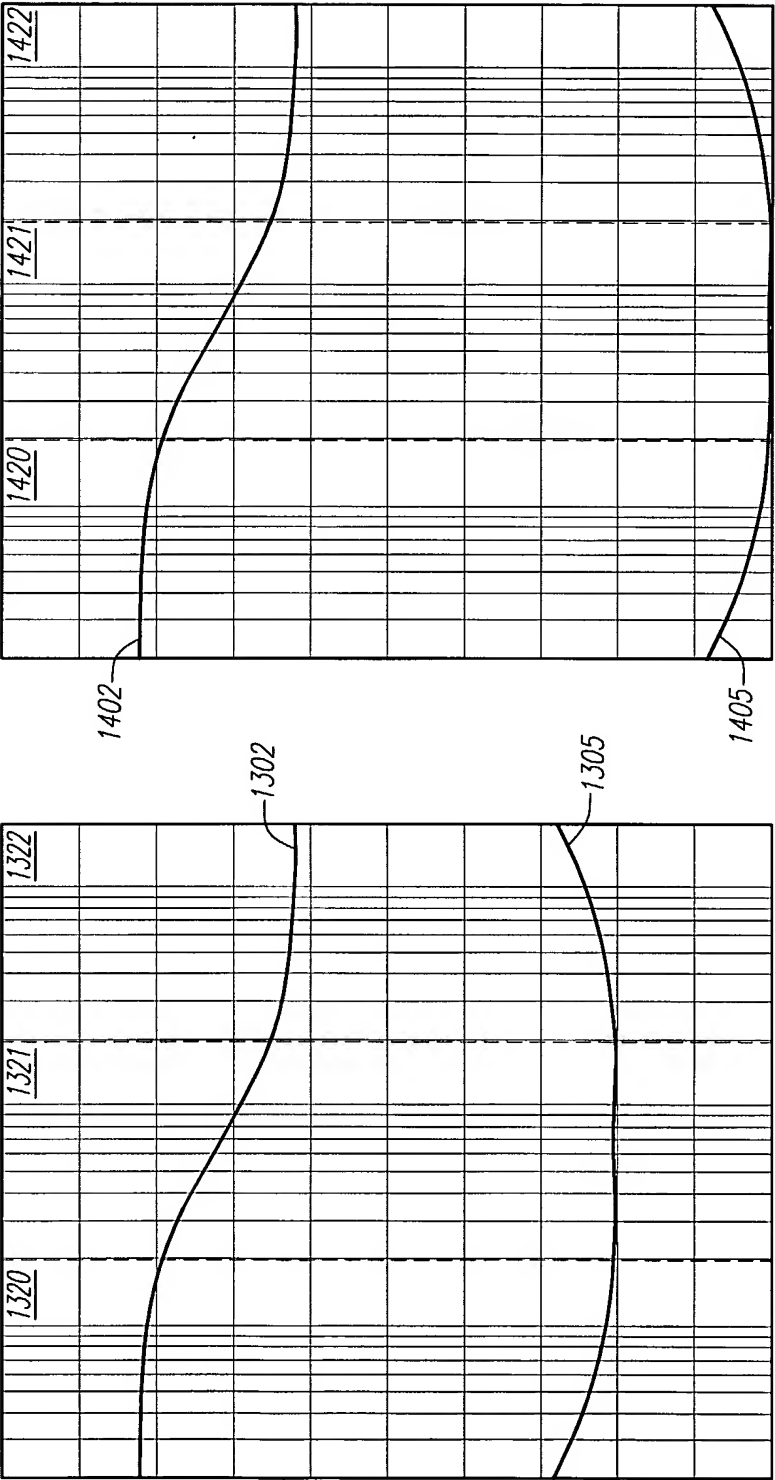


FIG. 14

FIG. 13

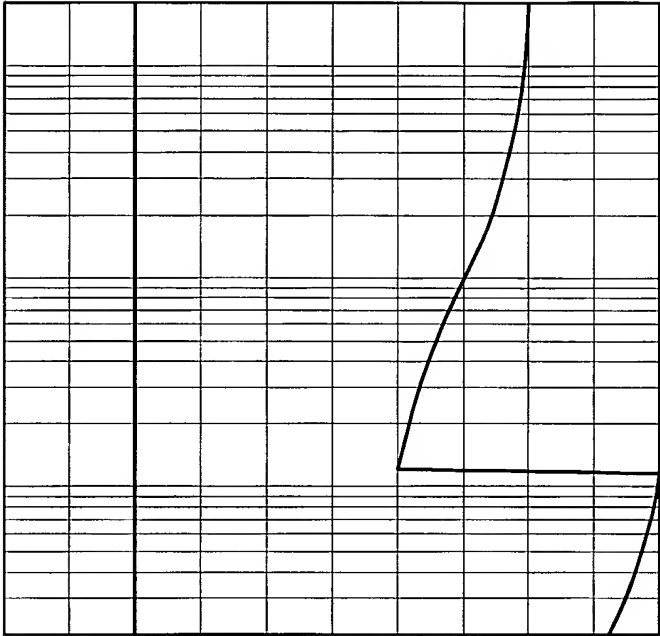


FIG. 15-2

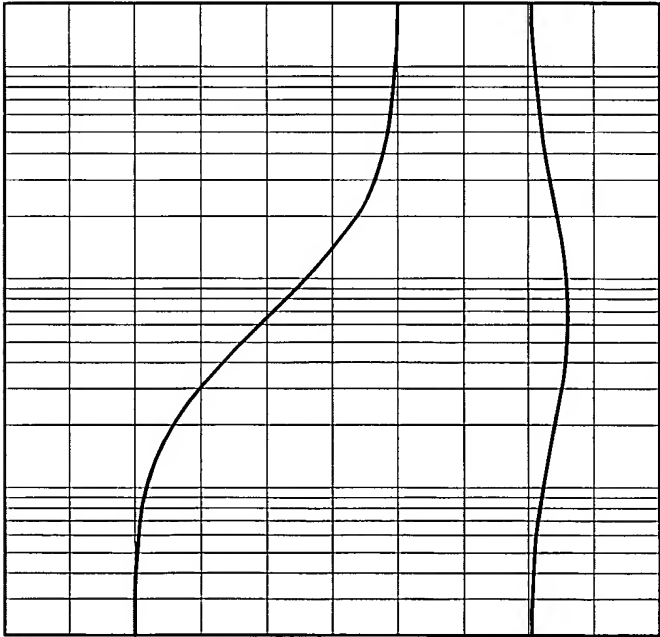


FIG. 15-1

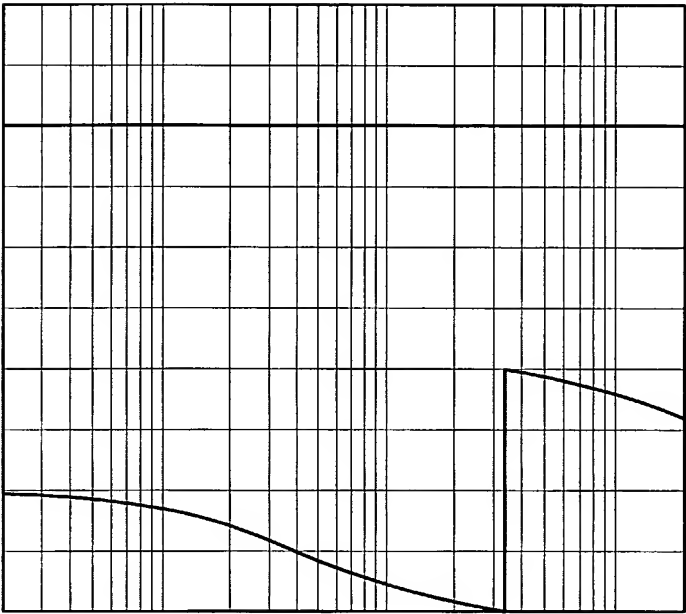


FIG. 15-3

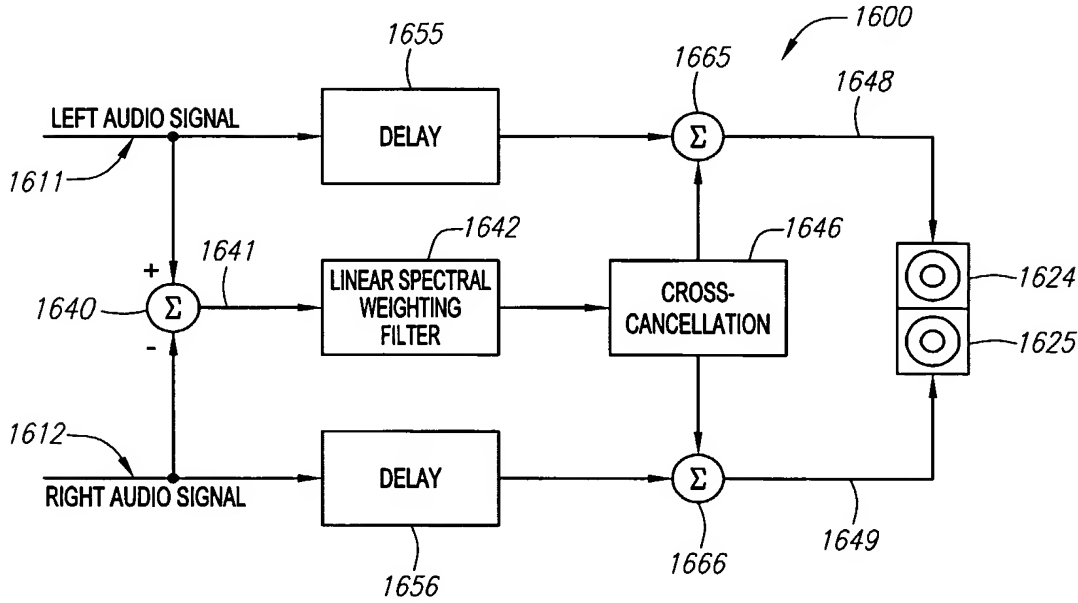
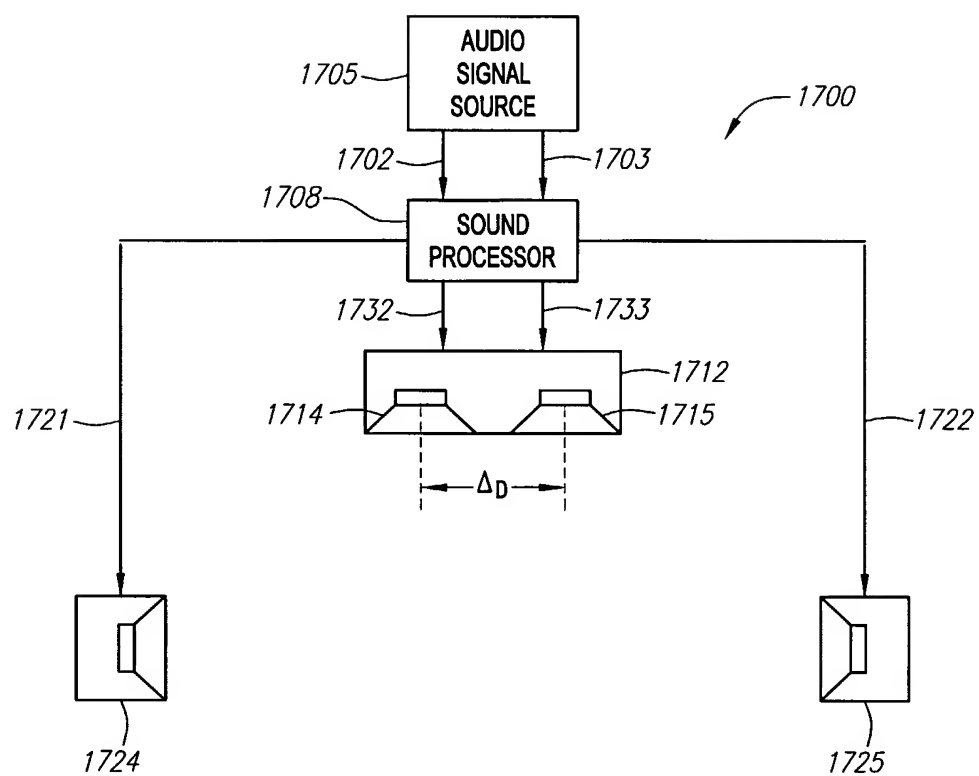


FIG. 16

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*FIG. 17*

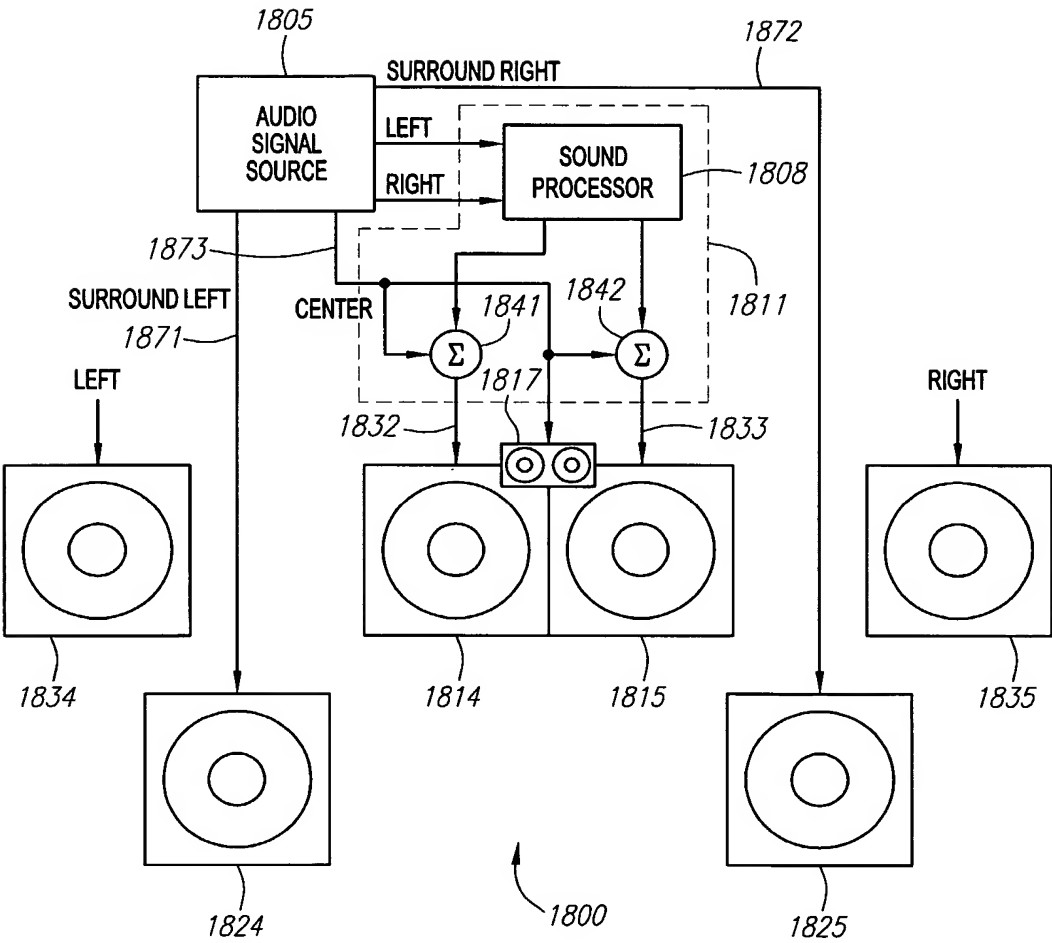


FIG. 18

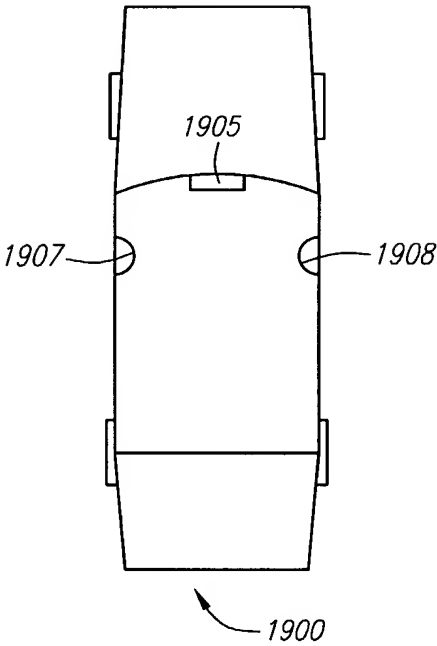


FIG. 19-1

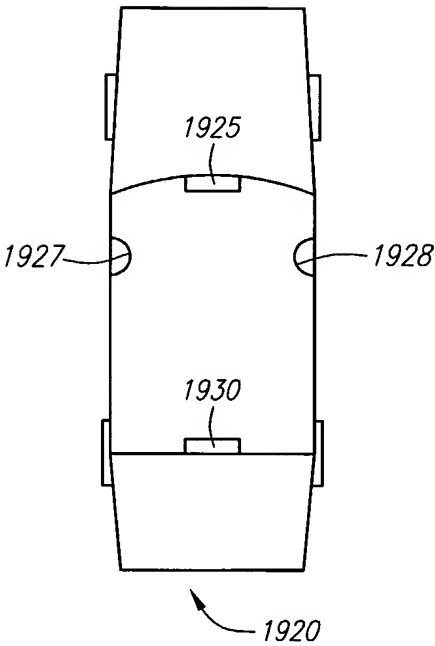


FIG. 19-2

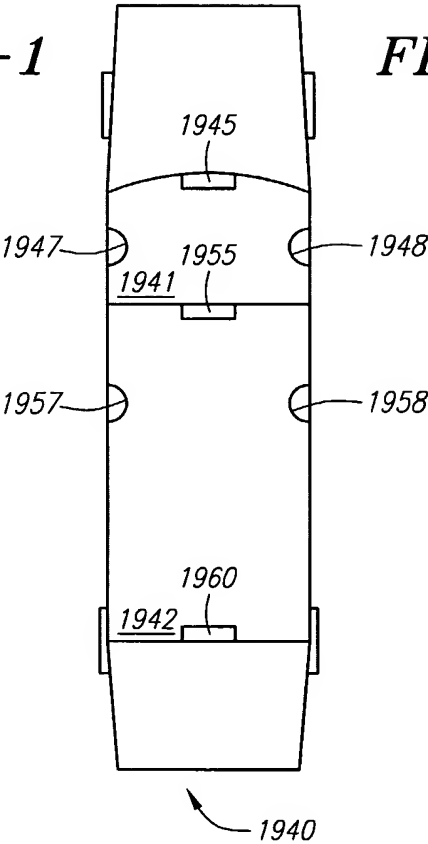
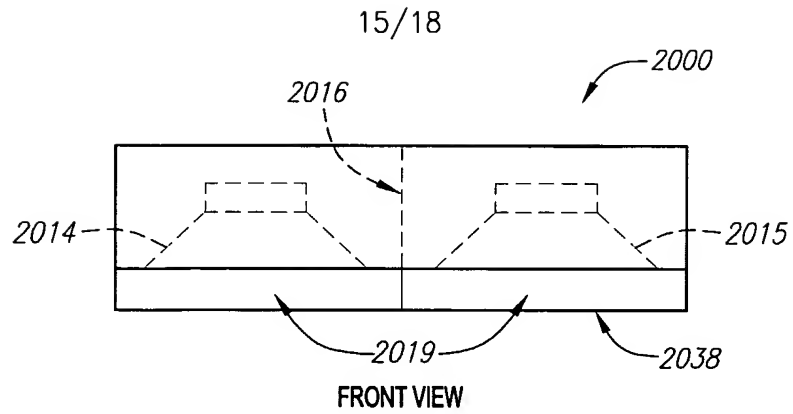
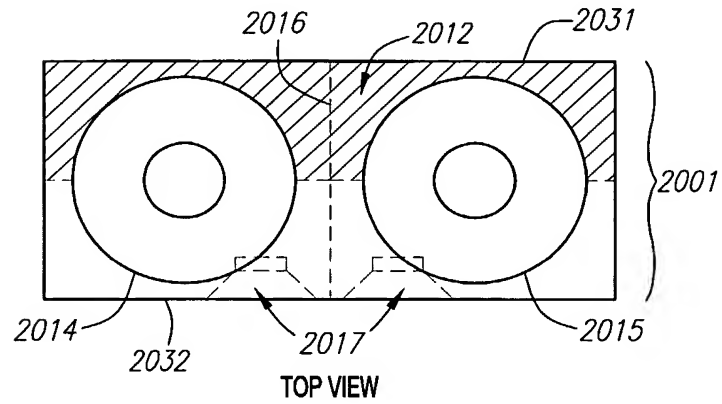


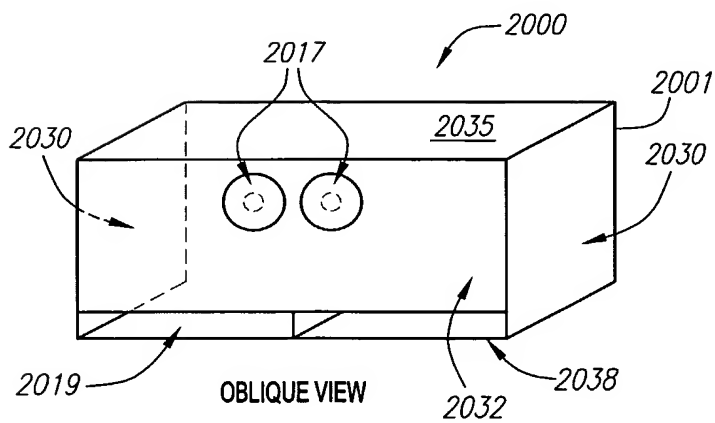
FIG. 19-3



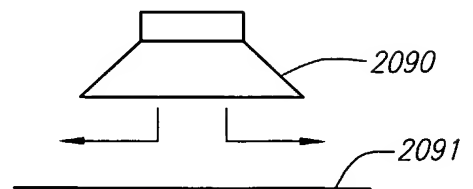
**FIG. 20-1**



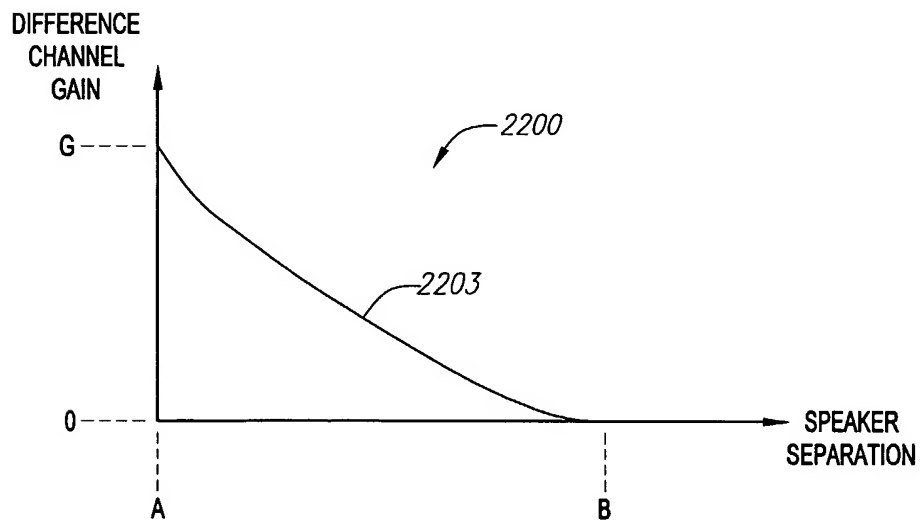
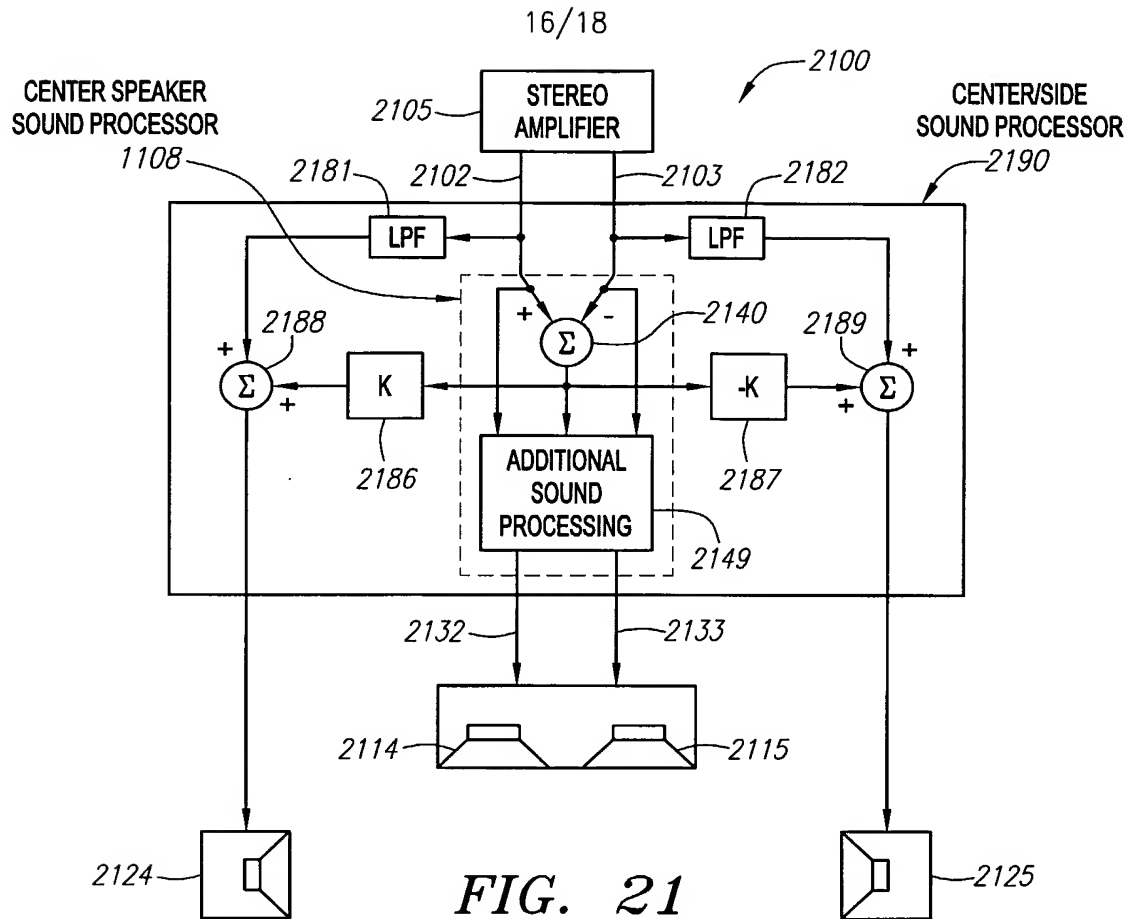
**FIG. 20-2**



**FIG. 20-3**

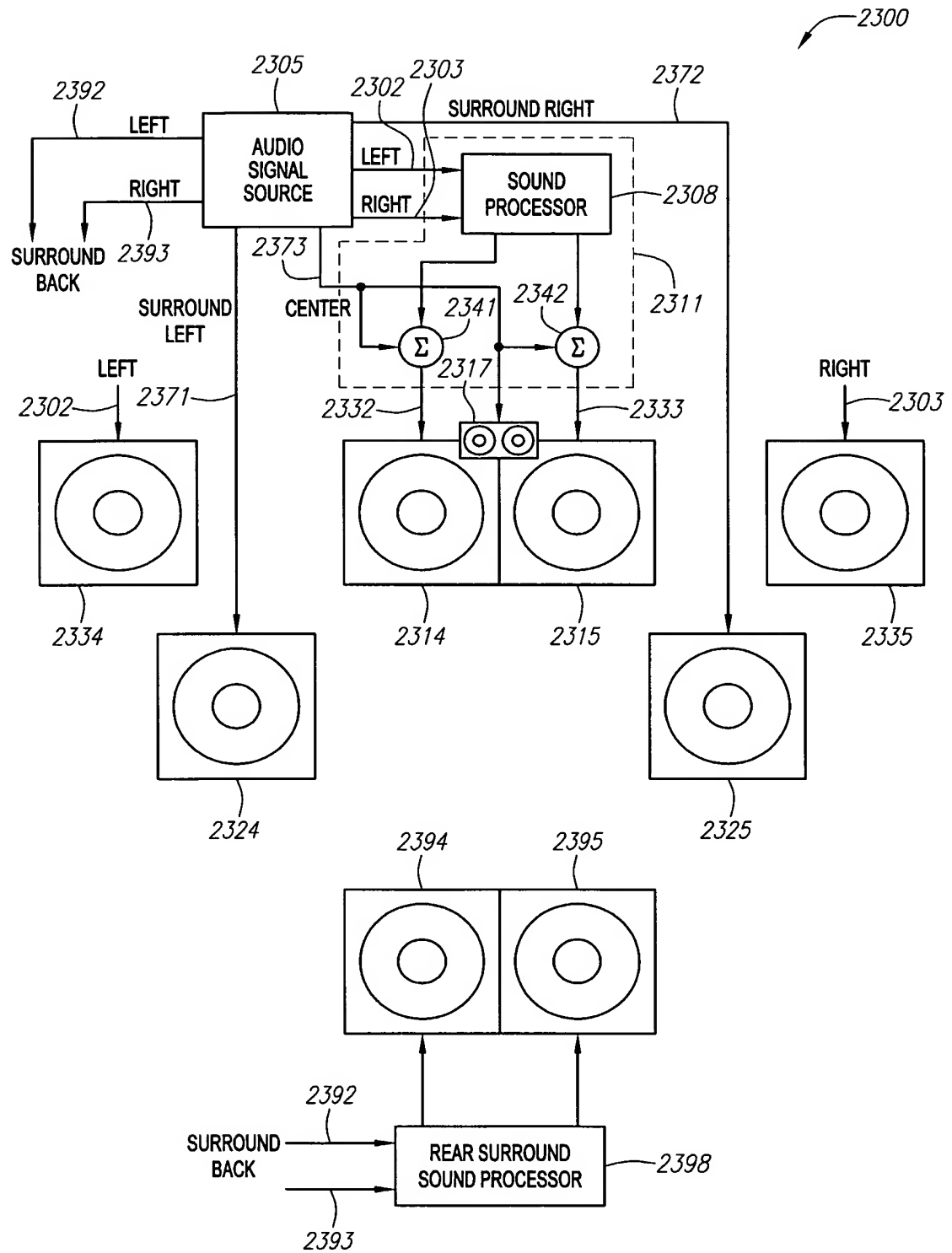


**FIG. 20-4**

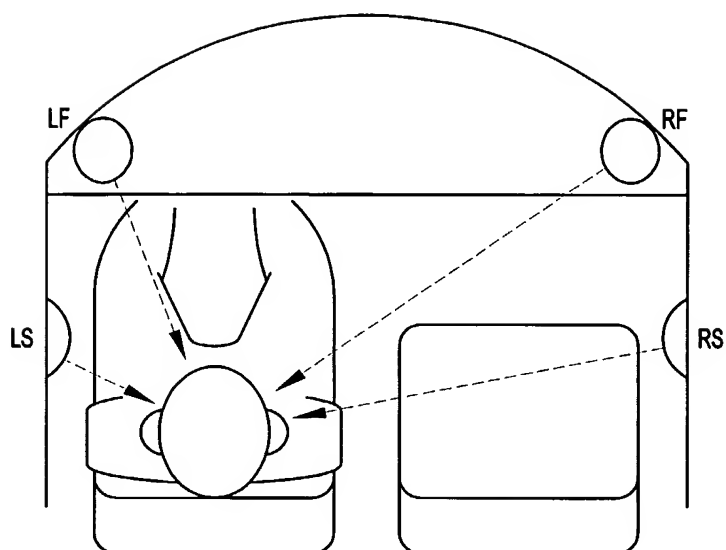


**FIG. 22**

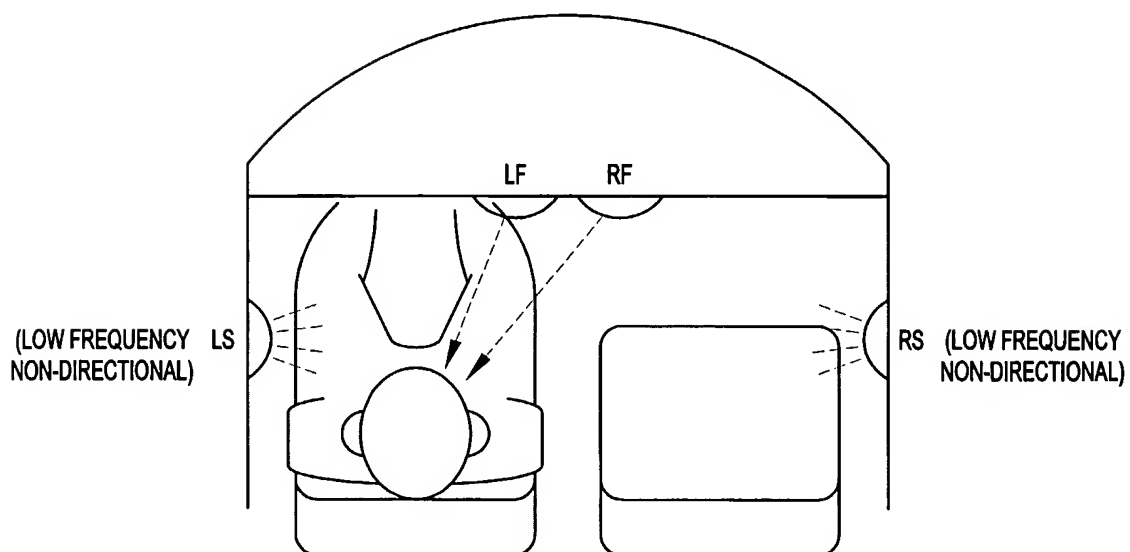
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**FIG. 23**

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**FIG. 24-1**  
(PRIOR ART)



**FIG. 24-2**

(19) World Intellectual Property Organization  
International Bureau



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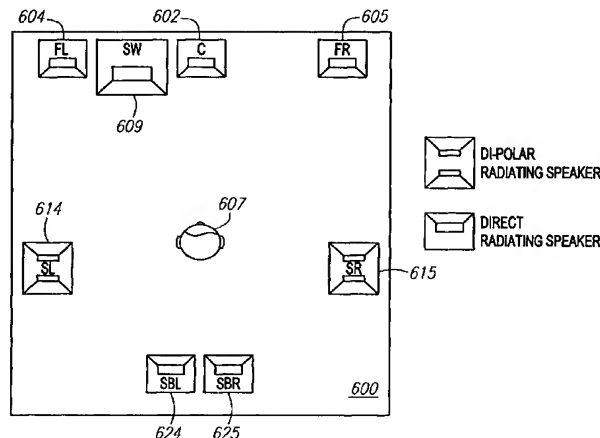
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Declarations under Rule 4.17:**

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for all designations
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations

[Continued on next page]

(54) Title: SOUND SYSTEM AND METHOD OF SOUND REPRODUCTION



(57) Abstract: A sound reproduction system comprises a left and right speakers located in close proximity, and a sound processor which provides audio signals to the pair of speakers. The sound processor preferably derives a cancellation signal from the difference between the left and right channels. The resulting difference signal is scaled, delayed (if necessary), and spectrally modified before being added to the left channel and, in opposite polarity, to the right channel. The spectral modification to the difference channel preferably takes the form of a low-frequency boost over a specified frequency range, in order to restore the correct timbral balance after the differencing process. Additional phase-compensating all-pass networks may be inserted in the difference channel to correct for any extra phase shift contributed by the spectral modifying circuit. The technique may be used in a surround sound system or an automobile sound system. In an automobile, the pair of speakers may be placed together in a common enclosure having a narrow slot near the base of the cone of the speakers. The speaker may be oriented perpendicularly with respect to the dashboard such that the sound emanates from the slot in the enclosure.



WO 02/065815 A3



**Published:**

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**(88) Date of publication of the international search report:**

7 August 2003

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 02/03880

## A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04S H04R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, EPO-Internal, PAJ

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Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>EP 0 404 117 A (LUCASARTS ENTERTAINMENT CO) 27 December 1990 (1990-12-27)</p> <p>page 2, line 4-9  page 4, line 13-23  page 4, line 49 -page 5, line 17  page 5, line 45 -page 6, line 32  page 6, line 56 -page 7, line 45  page 8, line 39-58  page 10, line 26-47  page 11, line 21-54</p> <p style="text-align: center;">--- -/--</p>	<p>1, 4-20,  28-37,  41,  43-48,  56, 60-66</p>

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Date of the actual completion of the international search

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Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	<p>PATENT ABSTRACTS OF JAPAN vol. 2000, no. 02, 29 February 2000 (2000-02-29) -&amp; JP 11 318000 A (ALPINE ELECTRONICS INC), 16 November 1999 (1999-11-16) abstract</p>	<p>1,21-28, 49-55</p>

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Information on patent family members

International Application No

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